Peatlands in Maputaland: Genesis, substrates and properties exemplified by the region of "Greater Manguzi"
– A basis for recommendations on sustainable cultivation, conservation and restoration

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Diplom Geograph Marvin Gabriel

Präsidentin der Humboldt-Universität zu Berlin
Prof. Dr.-Ing. habil. Dr. Sabine Kunst

Dekan der Lebenswissenschaftlichen Fakultät
Prof. Dr. Bernhard Grimm

Gutachter/innen

1. Prof. Dr. Jutta Zeitz
2. Dr. Alexandra Barthelmes
3. Dr. Donovan Kotze

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Think about the world you want to live and work in.

What do you need to know to build the world?

Demand that your teachers teach you that.

Pyotr Alexeyevich Kropotkin

Abstract

Peatlands in South Africa are important and threatened ecosystems. They are of great socio-ecological significance, as sources of freshwater, fertile land, material for construction, medicinal plants, habitat for specialised plants and animals, and as an attraction for ecotourists. Some 20.200 ha, about two thirds of South Africa's peatlands, are located at the Maputaland Coastal Plain. *Eucalyptus* plantations and common cultivation practices which include drainage are threatening the existence of the peatlands. A better understanding of the processes and properties of peatlands in Maputaland is necessary to develop effective protection strategies. This dissertation investigates peatland formation in Maputaland from a soil-related point of view, in order to identify the requirements for effective conservation and restoration measures, as well as more sustainable cultivation practices. Through a macrofossil analysis - a method which has not been applied in South Africa before - insights into the peatland- and peat formation processes were obtained. In a second step, based on the field examination of 141 soil profiles, 15 different peatland substrates were described and categorised into genetic substrate groups, and into botanical peat types. In accordance with the categorisation of the substrates, mean values for the following physical and chemical properties were determined: Carbon content, C/N ratio, electrical conductivity, pH-value, bulk density, pore size distribution, saturated hydraulic conductivity, unsaturated hydraulic conductivity and maximum capillary rise. Moreover, for the first time, the effect of degradation on the physical and chemical properties of South African peatlands was explored. Therefore, the aforementioned soil properties were measured for substrates at different degrees of degradation. Based on the changes in the soil properties thus established, the loss of ecosystem functions through degradation is discussed. By considering the frequency of occurrence of the substrate types in different hydrogeomorphic peatland types, adapted implications for conservation, restoration and cultivation are derived, in accordance with the established soil properties. In addition, based on the actual projections of climate change, estimations about future stress on the peatlands of the Maputaland Coastal Plain were derived.

Keywords: South Africa, peatlands, hydrogeomorphic wetland types, peat properties, peatland degradation, conservation

Zusammenfassung

Moore in Südafrika sind wichtige, aber bedrohte Ökosysteme. Sie sind von großer sozio-ökologischer Bedeutung: als Süßwasserspeicher, potentiell ertragreiches Ackerland, Quelle für traditionelle Baumaterialien und Medizinalpflanzen, Lebensraum für spezialisierte Tier- und Pflanzenarten sowie als Attraktion für ökologischen Tourismus. Etwa 20.200 ha, das sind zwei Drittel der südafrikanischen Moore, befinden sich auf der Küstenebene Maputalands (Maputaland Coastal Plain). Eukalyptusplantagen und gängige Anbaumethoden, die Dränung beinhalten, bedrohen die Existenz der Moore. Ein besseres Verständnis von Prozessen und Eigenschaften der Moore Maputalands ist dringend erforderlich, um effektive Schutzstrategien zu entwickeln. Diese Dissertation untersucht die Moorbildung in Maputaland aus einer bodenkundlichen Perspektive, um Voraussetzungen für effektive Schutzmaßnahmen und Renaturierungsmaßnahmen abzuleiten sowie Ratschläge für nachhaltigere Anbaumethoden auszuarbeiten. Mit einer Großrestanalyse, einer Methode, die in Südafrika zum ersten Mal angewendet wurde, sind Moor- und Torfbildungsprozesse untersucht worden. In einem zweiten Schritt wurden auf Grundlage von 141 in Feldarbeit untersuchten Bodenprofilen 15 unterschiedliche Moorsubstrate beschrieben und in genetische Substratgruppen sowie botanische Torftypen kategorisiert. Basierend auf dieser Unterscheidung der Substrate wurden die folgenden physikalischen und chemischen Bodeneigenschaften bestimmt: Kohlenstoffgehalt, C/N Verhältnis, elektrische Leitfähigkeit, pH-Wert, Trockenrohdichte, Porenverteilung, gesättigte und ungesättigte hydraulische Leitfähigkeit sowie maximaler kapillarer Aufstieg. Zudem wurden zum ersten Mal die Auswirkungen von Degradierung auf die physischen und chemischen Eigenschaften von südafrikanischen Mooren untersucht. Hierfür wurden die eben benannten Kenngrößen für Substrate in verschiedenen Degradierungsstufen gemessen. Auf Grundlage der Veränderungen der Bodeneigenschaften werden die Verluste von Ökosystemfunktionen durch Degradierung diskutiert. Anhand der Häufigkeit der Substrattypen in den unterschiedlichen hydrogeomorphologischen Moortypen werden angepasste Empfehlungen für Schutz, Renaturierung und nachhaltigere landwirtschaftliche Nutzung der Moore erarbeitet, basierend auf den ermittelten Substrateigenschaften. Darüber hinaus werden auf Grundlage aktueller Klimaprognosen zukünftige Stresssituationen für die Moore Maputalands durch den Klimawandel analysiert.

Schlagwörter: Südafrika, Moore, hydrogeomorphologische Moortypen, Torfeigenschaften, Moor Degradierung, Naturschutz

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Abbreviations

aggr.	Qualifier for aggregation horizon
AMS	Acceleration mass spectrometry
BD	Bulk density
BP	Before present
CVB	Channelled valley-bottom
C/N ratio	Total carbon to total nitrogen ratio
eart.	Qualifier for Earthification horizon
EC	Electric conductivity
FP	Flood plain
H	Referring to the von Post (1922) humification degree
HGMT	Hydrogeomorphic wetland types
ID	Interdune depression
LORCA	Long-term apparent rate of carbon accumulation
moor.	Qualifier for grainy moorsh horizon
OM	Organic matter
pf	Soil moisture tension
pf0	Total pore volume
shrin.	Qualifier for peat shrinkage horizon
SP	Seep
UCVB	Unchannelled valley-bottom
VAR	Vertical accumulation rate
VB	Valley-bottom
[N]	Sample size

1 Introduction

1.1 Peatlands in South Africa

Peat is a soil substrate with more than 30% organic matter, which is formed by the sedentary (i.e. in situ) accumulation of plant residues (Joosten & Clarke 2002). Usually this occurs where water saturation inhibits the mainly aerobic processes of decomposition, although other factors such as soil acidity and low temperature also reduce the activity of soil organisms. In addition, the presence of plant species with high contents of more persistent tissues such as lignin, waxes and resins is beneficial for peat formation (Koppisch 2001). Peatlands are ecosystems with a peat layer forming the upper soil (Joosten & Clarke 2002). Worldwide, different definitions are used to define the minimum vertical extent of the peat layer required for an area to be labelled peatland. In this dissertation peatlands will be regarded as such if the minimum vertical extent of the peat layer is 30 cm, a convention also used by Joosten & Clarke (2002).

Besides the term peatlands, other words are also commonly used to refer to an ecosystem with the same, or similar conditions. The term wetland refers to an area which is frequently inundated or saturated by water and which contains vegetation adapted to these conditions (Joosten and Clarke 2002). The term mire refers to a peatland which is currently accumulating peat (Joosten & Clarke 2002). All places where peat accumulation has stopped, for example due to drainage for cultivation, are called peatlands as long as peat layer of at least 30 cm remains. Because of South Africa's ethnic diversity, many other local names are also commonly used such as iDdobo (isiZulu) and vlei (Afrikaans).

South Africa has some 298 km² of peatlands (Marneweck et al. 2001). This figure accounts for only about 0.03% of the country's surface, which is a hundred times less than the global mean of 3% (Joosten and Clarke 2002). Peatlands are of great importance for carbon sequestration, accounting for as much as a third of the Earth's soil carbon storage (Joosten and Clarke 2002). Furthermore, with their great ability to store water, they account for about 10% of the world's freshwater resources (Joosten and Clarke 2002). Due to their small area, South African peatlands contribute little to global carbon sequestration. Nevertheless, on a regional level they fulfil many socio-ecological functions, such as - the provision of arable soil; as a resource for medicinal plants, craft materials, and materials for construction; as an attraction for eco-tourists; as protection against soil erosion; as an important habitat for endangered species; and as a landscape which, in itself, forms an important part of the cultural heritage (Kotze et al. 2008). The most important function on a local scale, however, is the retention of water (Grundling A. et al. 2016)[1]. South Africa as a relatively arid country has many areas where the evapotranspiration exceeds, by several times the precipitation, and therefore peatlands retaining the water in the landscape are most precious (Schulze 1997).

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[1] Two different authors with the name Grundling are cited in this work. For clarity, the works of author, Althea Grundling will be referenced in the main text as Grundling A. This excludes chapters 2,3 and 4, where the reference style follows the requirements of the journals.

Maputaland, a coastal plain lying in the South African province of KwaZulu-Natal, contains about 2/3 of the South African peatland areas. Reasons for this are a near-surface aquifer (Grundling A. 2014) and also relatively high precipitations of between 600 and 1100 mm per year, decreasing from the coast towards the interior (Maud 1980). Generally, the soils of the lowland part of the plain formed within a layer of unconsolidated aeolian distributed sand of Holocene origin (Maud 1980). Because of their poor suitability for cultivation, with low water retention capacities and few available nutrients, peatlands gain additional importance for local smallholders. When drained, the substrate has much higher water retention and cation exchange capacities than the surrounding soils, making drained peatlands apparently ideal sites for cultivation (Grundling A. et al. 2016). Because of this, there is a very close relationship between local communities and peatlands with people who live completely or partly from subsistence farming having a strong dependence on the peatlands (Sliva et al. 2004, Grundling A. et al. 2016, Pfister 2016).

Peatlands in Maputaland, however, face two big threats. One is the water table draw-down (lowering of the water table) caused by large scale *Eucalyptus* plantations and the other is drainage, commonly utilised for cultivation (Grundling A. et al. 2016). When the water level in a peatland is lowered and several vertical decimetres of the soil dry out, decomposition and mineralisation by aerobic soil organisms start to take place in those dry layers. Also, the risk of peat fires, like the ones in the Vazi peatland complex (Grundling & Blackmore 1998), increases drastically, and therewith the risk of losing the complete ecosystem with all its benefits.

It was in order to identify risks, such as these, which imperil the functioning of wetland ecosystems, that a project named AllWet-RES was initiated. Besides investigating threats to the wetland ecology and assessing related social effects, the project also aimed to recommend various solutions for their mitigation.

1.2 AllWet-RES

This PhD thesis is part of a DAAD-project named AllWet-RES – *Alliance for Wetlands Research and Restoration* (project no. 55516208), a research initiative between the Humboldt-Universität zu Berlin, the Technische Universität München, the University of the Freestate, the University of Zululand, and the Agricultural Research Council. It was financed by the German Federal Ministry of Education and Research (BMBF). The project ran between August 2012 and December 2015. With an interdisciplinary approach, including social sciences, soil science, landscape architecture and restoration ecology, AllWet-RES aimed to identify socio-ecological pressure on wetlands and come up with practical solutions for wise use and sustainable management of wetlands, together with alternative sources for income generation and improvement of fertility in non-wetland soils. For several reasons, the focal point for the field-study investigations was the town of Manguzi, in the north of the South African part of the Maputaland Coastal Plain. Lying some 13 km south of the Mozambican border and 11 km from the Indian Ocean, Manguzi is one of the few towns in the region with a developed infrastructure and with facilities such as internet access and a library.

Moreover, the non-governmental organisation Tholulwazi Uzivikele, which resides in Manguzi, was a key partner for student projects. In and around Manguzi there exist a large number of peatlands and wetlands in valley-bottoms and dispersed interdune depressions. These peatlands are used as vegetable gardens, in particular, and also for crop production on a commercial scale. Manguzi lies in close proximity to the Kosi Bay Lake System, a renowned Ramsar site within iSimangaliso Wetland Park, which is, a UNESCO world heritage site. Many peatlands between Manguzi and the Indian Ocean lie in the watershed of the Kosi Lake System, both inside and outside the boundaries of the iSimangaliso Wetland Park.

The part of the Humboldt-Universität zu Berlin in this project was the investigation of peatland soil qualities, in order to contribute to the development of recommendations on sustainable management of peatlands and restoration measures. In addition, these recommendations and measures had to be adapted to the regional landscape ecological conditions.

1.3 State of knowledge

Until the 1990s little scientific work was conducted on South Africa's peatlands. Noble (1974) describes the existence of peat-containing ecosystems in South Africa, and classifies them, according to geomorphic and botanical factors, as swamps, sponges, springs, pans, vleis (fens) and bogs. The last category is dubious, as bogs rely exclusively on rain water, and precipitation in this area is considerably lower than the potential evapotranspiration (Schulze 1997). Even high altitude mires in Lesotho, where precipitation is higher and evaporation lower than in other regions of southern Africa, are referred to nowadays as fens (Grundling et al 2016). Other authors also acknowledged the existence of peatlands in South Africa, fundamentally following the categories of Noble (1974), and essentially with the aim of giving overviews of aquatic ecosystems rather than with the intention of exploring them in further detail (Huntley 1978, Thompson & Hamilton 1981). Until the late 1980s the deepest insights into peatlands were yielded by paleontological works, which used peat deposits with preserved pollen as proxies for past vegetation and climate changes (e.g. Martin 1968, Butzer & Helmgren 1972, Schalke 1973, Scott 1982). Moreover, these works did not focus on the study of the peatlands themselves. Meadows (1988) published an article which built upon the findings of the paleo-investigations and peatland initiations in South Africa. However, none of the peatlands of Maputaland were included in that research, although their existence was known. In Begg (1980) peatlands are mentioned as a source of peat-stained water into the Kosi Lake system, but they are not described. In 1989 the South African *Council for Geoscience* became actively involved in the mapping and characterisation of peatlands in northern KwaZulu-Natal (Grundling et al. 1998). In this context, Smuts (1992) investigated "Peatlands of the Natal Mire complex", including the differentiation of some peatland types, and this was followed by the article "Peat and peatlands in South Africa: Characterisation and quantification" in the *Journal of Energy in South Africa* (Smuts 1996). These works were undertaken to evaluate peat as a possible renewable source of fuel. Based on his investigations, Smuts (1992) differentiates mires, by their peat-forming vegetation, into forest mires and reed/sedge mires. He further devides forest mires into mangrove mires, *Raphia* mires and hard wood mires; and reed/sedge mires are further devided into *Papyrus* mires, sedge mires, *Schoenoplectus* mires, *Phragmites* mires and *Typha* mires (Smuts 1997). Ever since this time Smuts (writing in 1992, 1996 & 1997) has remained the only person to have investigated mangrove peatlands in Maputaland. Mangroves, being unsuitable for crop cultivation, and being hydrologically influenced rather by sea-level rather than by land use, will not be investigated in this study; however, it should be noted that they are locally threatened by various human uses and climate change (Traynor & Hill 2008, Lovelock et al. 2015, Macamo et al. 2016).

Investigating the possible use of peat as fuel, Smuts (1992 & 1996) determined the calorific values of peat substrates for the different mire types he described. He found that the average value lies at 16.5 MJ/kg, with reed-sedge peat having the highest values - usually between 20 and 25 MJ/kg. He also mentioned peat accumulation rates (as personal communication with a third person) of up to 100 mm/year, and he concluded “Reed-sedge peatlands are considered to be an alternative energy supply option in the region as large volumes occur extensively, regeneration is quick and rehabilitation will be fast and complete” (Smuts 1992). Thamm et al. (1996) derived peat accumulation rates of a maximum of only 19 mm/year. This figure was acquired by examining exotic pollen species in peat soil profiles. The more reliable C14 dating method, however, yielded results far below the ones from Smuts (1992) and Thamm et al. (1996) and put an end to the discussion. Grundling et al. (1998 & 2000) concluded that with an average accumulation rate of 1.06 mm/year, South African peat cannot be considered a renewable resource on a human timescale.

In the late 1990s and the early 2000s, Grundling et al. (1998 & 2000), Marneweck et al. (2001), Grundling (2001) and Grundling & Grobler (2005) further investigated the distribution and character of South African peat resources, concluding that about 2/3 (ca. 20.200 ha) are located in Maputaland. The biggest peatland complex is the delta of the Mkuze River, with about 8.800 ha. Other peatland complexes are the Muzi swamp, and complexes associated with coastal lakes such as Lake St. Lucia, Lake Sibaya and the Kosi Bay Lakes. According to Grundling et al. (1998) papyrus-reed-sedge mires are most common, occupying 55% of the total mire surface, and these are followed by peat swamp forests at 30%, and grass-sedge mires at 15%. About 65% of the peatlands are shallower than two metres. Peat substrates with an organic matter content of between 85% and 95% make up only a few percent of the total, whereas in general peat substrates with organic matter contents of between 55% and 70% are found. On the one hand, these results reflect high proportion of the mineral fraction in the peat, which is due to the very dynamic dune environment of the coastal plain, with aeolian sand transport. On the other hand, the results also reflect a poor differentiation between substrate types. Gyttja, a limnic sediment of terrestrialising lakes, and one which usually has a lower content of organic matter than peat, was counted as peat as well. Since the proposed mire scheme by Smuts (1997), no other studies were undertaken with the intention of classifying peatland substrates or determining their physical and chemical properties. The South African Soil Classification System, “The Blue Book” (Soil classification Working Group 1991), merely differentiates between fibrous and humified organic material. Some of the aforementioned studies used botanical or genetic categories to refer to certain substrates, but neither did they follow the same nomenclature, nor did any of the publications focus on the entirety of existing peatland substrates.

Next to the South African Soil Classification System, Ollis et al. (2013) elaborated the “Classification system for wetlands and other aquatic ecosystems in South Africa”. This classification approach includes the distinction between different hydrogeomorphic units. Based on this, Grundling A. (2014) investigated wetlands and peatlands in northern Maputaland in different hydrogeomorphic settings. In her results she distinguishes between temporary and permanent wetlands. Permanent wetlands, when not directly underlaid by clay, owe their existence to contact with ground water, and their water tables fluctuate less than two metres throughout different hydroperiods. Under these conditions, peatlands are commonly encountered (Grundling A. 2014). Three hydrogeomorphic settings were identified as flow-through regimes in contact with a shallow aquifer: depressions, valley-bottoms, and seeps (on slopes). The most stable water conditions are found in drainage lines, where the water table usually fluctuates less than 0.1 metres throughout different hydroperiods. Hence, peatlands are common in channelled valley-bottoms (Grundling A. 2014). Another hydrogeomorphic setting was investigated by Turner & Plater (2004) and Ellery et al. (2012). Peatlands in the area of the Mkuze swamp in southern Maputaland principally formed when tributaries of the Mkuze River were cut off due to sedimentation. The remaining inundated valleys became lakes which filled with gyttja and peat.

Grundling et al. (2013 & 2015) investigated the development and water balance of the Mfabeni Mire close to St. Lucia, which, at 11 metres and with an age of 45.000 years, is the deepest and oldest mire in Maputaland and in South Africa. The authors found that the Mfabeni Mire is an important regulator of the regional water table, as the peat formation in the valley increases the water level in the surrounding areas. They concluded that this flow regulation effect is of great importance for the buffering of hydroperiods and prevents adjacent wetland ecosystems from drying out in the dry season. Grundling (2014) stated that climate change, with more frequent extreme weather events and less recovery time in between, will put a higher level of stress on these ecosystems, probably exceeding the buffering capacities and leading to degradation (Grundling 2014).

Besides the threats from climate change, peatlands and wetland ecosystems face the aforementioned peril from land use. Sliva et al. (2004) and Grobler et al. (2004) stated that drainage of peat swamp forests for cultivation, together with a growing population pressure, is a great threat to the peatlands in rural Maputaland. They further outlined the necessity of introducing a proper management plan for peatlands in Maputaland, in order to conserve them and to maintain their benefits for local communities in the future. However, for adequate management plans, as well as conservation and restoration issues, many important issues are insufficiently investigated.

Drainage and water table draw-down lead to the exposure of peatland areas to aerobic conditions. It is known from studies in the northern hemisphere that the physical and chemical properties of peat are changing with increasing degradation (Ilnicki & Zeitz 2003). With the exposure to aerobic conditions, a process of secondary soil formation is initiated. Peat soil becomes subject to compaction and mineralisation. There occurs a shift in the pore size distribution and a progressive decrease in total porosity, saturated conductivity, and carbon content. (Schwärzel 2000, Zeitz & Velty 2002, Ilnicki & Zeitz 2003, Kecharvarzi et al. 2010, Szajdak & Szatyłowics 2010). Neither have all of these soil properties previously been investigated for peatlands in South Africa, nor does there exist a comparative study comprising the entirety of peatland substrates, or exist a study investigating the effects of peat soil degradation on these properties. To close these research gaps is the main intention of this dissertation.

1.4 Research objectives

The evaluation of ecosystem functions and the ecosystem sensitivities of different peatland types are important pillars for conservation. They can show which ecosystems should be given conservation priorities and can help to define effective conservation measures. Knowledge about the typical substrate compositions of peatlands and their properties is needed for the evaluation of functions such as water storage, flow regulation, water availability during dry spells and carbon sequestration. Also knowledge about peat-forming plant communities is needed, so that conservation priority can be given to wetlands with potentially peat-forming vegetation.

For hydrological restoration issues, it is important to investigate which measures are most suitable for each peatland type. Furthermore, it is necessary to know which plant species are the main peat producers, in order to enhance the presence of these species in recovering sites. In addition, more knowledge on the alteration of peatland substrates during degradation processes is needed, in order to anticipate the response to re-wetting measures of the different peatland types, and in order to be able to foresee the response at different stages of degradation.

To assess the implications on cultivation it is also necessary to investigate the hydrology of the different hydrogeomorphic peatland types. Such investigation is important, partly for the evaluation of the impacts of common cultivation practices – in particular the impact of drainage- and also in order, if possible, to identify the peatland zones where the impact of cultivation is minor. In that context, the relation between substrate properties and peatland degradation is of great importance.

With regard to the requirements necessary for the protection of peatlands, five research objectives were phrased:

Objective 1: Genesis
To investigate the peatlands' genesis and the processes that drive peat formation in Maputaland. Further, to investigate peat-forming plant species, peat accumulation rates and long term carbon sequestration rates for different peatland substrates.

Objective 2: Substrates and classification
To create an overview of peatland substrates in Maputaland, classify them into genetic substrate groups and botanical peat types, and indicate which substrates' typically occur in the various hydrogeomorphic types.

Objective 3: Substrate properties
To determine standard soil properties for the existing peatland substrates, such as organic matter content, bulk density, C/N ratio and pH-values. Furthermore, physical-hydrological parameters, such as pore size distribution, saturated hydraulic conductivity, unsaturated conductivity and capillary rise shall be determined as well.

Objective 4: Effects of degradation on soil properties
To determine the parameters of objective 3 for substrates with differing degrees of degradation.

Objective 5: Consequences of predicted climate change
To derive the likely hydrological consequences of the predicted climate change on peatlands in different hydrogeomorphic settings.

1.5 Structure of the dissertation

The main body of this work is divided into six chapters. Chapters 2, 3 and 4 are written as stand-alone scientific articles. Each focuses on one or more research objectives and contains its own set of aims and questions in order to investigate the research objective. Chapters 2 and 3 have already been published in peer-reviewed journals. Chapter 4 is submitted for publication. The content of the chapters is as follows:

CHAPTER 2 deals with research objective 1, above. It investigates the genesis of peatlands and peatland substrates, as well as the drivers for peat formation in Maputaland, through a high resolution macrofossil analysis of two peat cores - one from an interdune depression peatland, and the other from an unchannelled valley-bottom peatland. This article - named "The development pathways of two peatlands in South Africa over the last 6200 years: Implications for peat formation and palaeoclimatic research" - was published in *The Holocene* (Gabriel et al. 2017a).

CHAPTER 3 deals with research objectives 2 and 3, above. It focuses on the typical peatland substrates of different hydrogeomorphic types, based on the results of the peat accumulation characteristics given in Chapter 2. In accordance with to the substrates encountered and their occurrence in the different hydrogeomorphic wetland types, a substrate reference scheme is proposed. This article - named "Peatland substrates in northern KwaZulu-Natal – A study of the forming environments, the properties and an approach towards classification" - was published in the *South African Journal of Plant and Soil* (Gabriel et al. 2017b).

CHAPTER 4 deals with the research objective 3 and 4, above. It analyses changes in the physio-hydrological properties of peatland substrates, due to degradation. In this way, the substrates described in Chapter 3 are characterised in greater detail with regards to water retention and permeability. Based on the typical formation environment of the different peatland substrates, implications considering vulnerability, conservation and mitigation of degradation as an effect of land use are derived for peatlands in different hydrogeomorphic wetland types. The manuscript for this chapter is named “Physical and hydrological properties of peat as proxies for degradation of South African peatlands – Implications for conservation”, and it has been submitted to the journal, *Mires and Peat.*

CHAPTER 5 deals with research objective 5 and discusses the likely effects of climate change on the peatlands of the Maputaland Coastal Plain.

CHAPTER 6 provides a synthesis of the work with recommendations regarding conservation, cultivation and restoration.

1.6 Field campaigns

Altogether, three fieldwork campaigns were conducted by the author, each in collaboration with a Masters student. The first campaign took place between October-December 2012 in company with Masters student Kilian Walz, whose M.Sc. Thesis was titled – “Charakterisierung und Vergleich verschiedener Moorstandorte unter Berücksichtigung der Landnutzungsintensität in Kosi Bay, Südafrika“ (Characterisation and comparison of different peatland sites with regards to land use intensity in Kosy Bay, South Africa)(Walz 2014). The second fieldwork campaign between October 2013 and March 2014, was undertaken with the assistance of Masters student Franziska Faul, whose M.Sc. Thesis was titled: “Physical Properties of Peatlands in Northern Kwazulu-Natal, South Africa, Implications for Management Practices” (Faul 2014). Faul was also the main author of a co-published article (Faul et al. 2016), which can be found in the appendix. The third fieldwork campaign was conducted between October 2014 and March 2015 together in the company of two Masters students - Camelia Toader, who wrote her M.Sc. Thesis with the title: “Pedologic and Stratigraphic Studies of Two Degraded Peatlands in Maputaland, South Africa” (Toader 2016), and Judith Pfister, who called her M.Sc. Thesis “Sustainable Use of Wetlands in Northern Kwa-Zulu Natal – Linking Soil Properties, Crops Physiology and Land Use” (Pfister 2016).

2 The development pathways of two peatlands in South Africa over the last 6200 years: Implications for peat formation and palaeoclimatic research

Marvin Gabriel[1], Mariusz Gałka[2], Lulu Pretorius[3] & Jutta Zeitz[1]

[1]Humboldt-Universität zu Berlin, Division of Soil Science and Site Science

[2] Adam Mickiewicz University in Poznan, Department of Biogeography and Palaeoecology

[3] University of the Free State in Bloemfontein, Centre for Environmental Management

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Abstract

For the first time plant macrofossil analysis supported by detailed stratigraphic studies was used to reconstruct peatland development in South Africa. Two peat cores (469 cm and 150 cm) from two coastal peatlands in KwaZulu-Natal were analysed for carpological macrofossils, wood and macrocharcoal. The first one, Matitimani, is an unchannelled valley-bottom peatland (site VB) and the second one, KwaMazambane, an interdune depression peatland (site ID) further up in the same catchment. Radiocarbon dating reveals that the peatland initiation at site VB at about 6260 cal yr BP. Rising sea-level and humid climatic conditions during that time coincide with the formation of organic gyttja (predominantly aquatic seeds like Nymphaea sp.). In ca. 4950 cal yr BP a change to drier condition took place, revealed by the formation of radicell peat from Cyperaceae, and an increase of fire frequency (macrocharcoal). After ca. 1200 cal yr BP peat swamp forest emerged, with Ficus trichopoda, Syzygium cordatum and Voacanga thouarsii forming wood peat. Site ID dates back to ca. 920 cal yr BP. Its initiation is assumingly related to reduced drainage capacities of the catchment subsequently to the peat formation in Matitimani. A steady change from gyttja forming communities (Nymphaea sp. – Eleocharis dulcis) to radicell peat-forming Cyperaceae-communities took place. The long-term apparent rate of carbon accumulation (LORCA) is higher for site ID (89 gCm2yr -1) than for site VB (55 gCm2yr -1). Except for the peat swamp forest period, fire occurred frequently at both sites; however less in environments with frequent inundations.

Keywords: carbon accumulation rates, charcoal, palaeoclimate, peat formation, plant macrofossils, South Africa

2.1 Introduction

Even though South Africa is regarded as an arid country (497 mm mean precipitation), there are some regions where peatlands can be encountered (Grundling and Grobler, 2005). Approximately 2/3 of those peatlands are situated on the Maputaland Coastal Plain in the KwaZulu-Natal province (Grundling et al., 1998). Peatlands face a lot of threats in this region, specifically through cultivation practices which include topsoil drainage of peat bodies, and the large scale expansion of Eucalyptus plantations in the catchments of the peatlands, which deplete the local groundwater and expose peat soil to mineralisation (Grobler et al., 2004; Pretorius, 2014; von Roeder, 2015). As peatlands fulfil valuable ecological functions and services for the local communities, conservation and renaturation efforts are needed to prevent further harm (Grobler et al., 2004). Research is needed to prepare a better basis for the successful protection of peatlands. Many aspects about these peatlands such as the geneses, the peat-composing plant species, the drivers of peat-formation, the peat accumulation rates, the diversity of peat-types, and their physical and chemical properties are not fully understood. Undisturbed peat deposits with fossil plant residues are archives providing unique information on environmental conditions and changes throughout a peatland's development (Gałka et al., 2017; Mauquoy and van Geel, 2007). Further, information on peat accumulation rates can be useful to calculate recovering times after degradation, as well as to estimate carbon sequestration rates of peatlands (Turunen et al., 2002).

Thus far, peatland initiation has been determined for eleven peatlands on the Maputaland Coastal Plain. All are of Holocene origin and younger than 10.000 BP, except for two peatlands - namely the Mfabeni- and Mhlanga-peatlands (ca. 45.100 BP and ca. 35.000 BP, respectively) (Grundling et al., 2000; Turner and Plater, 2004. Except for Mfabeni, the studies do not consider the peatland's stratigraphies and substrate types, hampering more detailed analyses of their development.

Palaeoecological works focusing on peat formation in South Africa are scarce. A study carried out by Turner and Plater (2004) stated that peat formation in a tributary valley of the Mkuze River was triggered by the isolation from the riverbed through sediment accumulation some 1400 years ago. This scenario, however, does not explain peatland initiations in other hydrogeomorphic settings. Other palaeoecological studies on the Maputaland Coastal Plain were carried out by Finch and Hill (2008) and Neumann et al. (2008, 2010). Here pollen analysis was used to investigate palaeoenvironmental changes by reconstructing shifts of vegetation types. However, pollen are subject to atmospheric transport, and pollen analysis therefore rather depicts overall vegetation development on the Maputaland Coastal Plain; whereas peatlands are much more azonal features. For the reconstruction of peatland development macrofossil analysis is a better tool, as it examines the in-situ residues of the place itself (Gałka, 2014; Mauquoy and van Geel, 2007). Furthermore, the application of plant macrofossil analysis in palaeoecological reconstruction has allowed the recognition of fossil plant remains to species level, which is limited in the case of pollen analysis (Birks, 2000; Feurdean and Bennike, 2008).

In the northern hemisphere macrofossil analysis is long known as a primary source to provide insights into peatland and lake development, and to identify peat building plant species (Grosse-Brauckmann, 1972, 1974; Katz and Katz, 1946;). Fossil fruits and seeds in South Africa have been studied so far only in the context of archaeological works (Sievers, 2015; Sievers and Muasya, 2011; Wintjes and Sievers, 2006).

In order to get new insights, detailed plant macrofossil analysis was applied to two peatlands, each representing a characteristic hydrogeomorphic wetland type of the Maputaland Coastal Plain. Four objectives were enunciated: i) to investigate the initial process of peatland formation; ii) to explore the influence of climatic changes on peatland development, especially with regards to their substrates; iii) to compare the geneses of the two peatlands concerning substrate composition and vegetation communities in different periods of substrate accumulation; iv) to calculate accumulation rates for different substrates.

2.2 Study area and study sites

The study area lies in the catchment of the Kosi Bay lake system, approximately 6 km from the Indian Ocean (Figure 2-1). This lake system falls within the Maputaland Coastal Plain, which stretches from Maputo in Mozambique 300 km south to the town Mtunzini (Grundling, 2014).

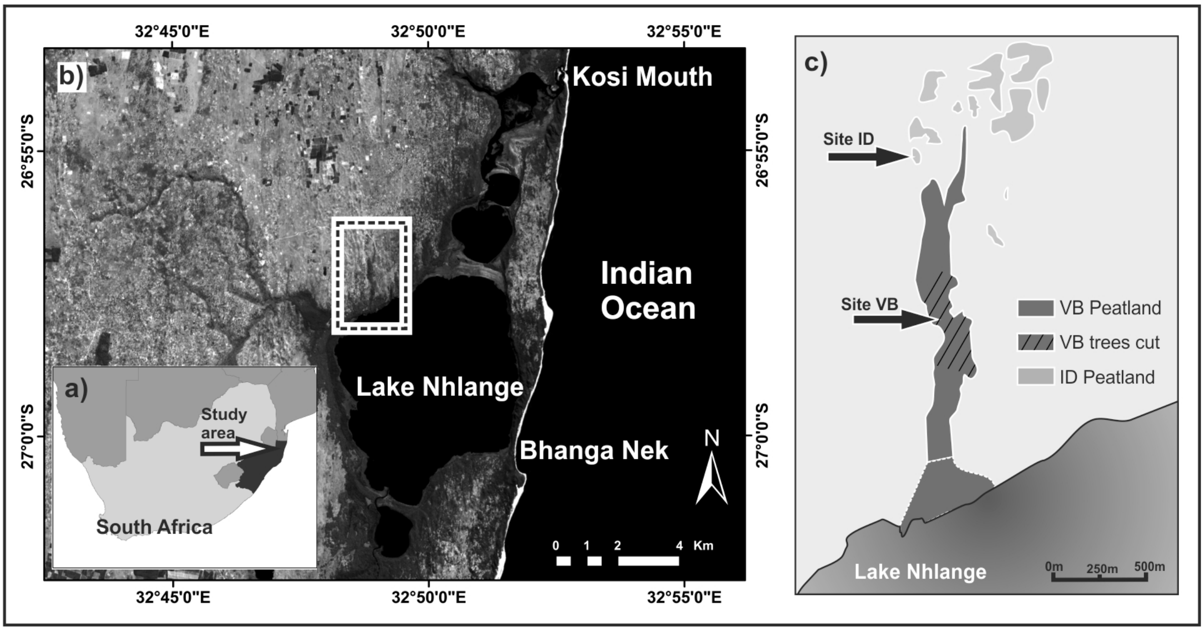

Figure 2-1: Map of the study area: **(a)** the location of the study area within the province of KwaZulu-Natal (black) in South Africa; **(b)** the setting of the study area around the Kosi-lake system (based on a SPOT 2012 image); **(c)** the distribution of peatlands within the highlighted box in **(b)** and the two study sites.

The climate is a transition from tropical to subtropical with two main influences: the Agulhas Current with warm sea surface temperature and the southward shift of the Intertropical Convergence Zone in summer (Neumann et al., 2010; Stager et al., 2013). Summers are hot with average maximum of 26°C in February and the winters mild with average 17°C in June (Lubbe, 1997). The potential annual evapotranspiration reaches between 2000 and 2200 mm (South African evapotranspiration map). The precipitation is about 950 mm with 60% of it between November and March (Grundling, 2014). Rainfall events with abundant precipitation are usually related to so called cut-off low pressure systems, which lead to strong convection (Singleton and Reason, 2007). More exceptional are extreme rainfall events related to tropical cyclones in the Mozambique Channel, e.g. cyclone Danae in 1976, with 700 mm (Grundling, 2014; Hughes et al., 1992; Kovàcs et al., 1985; Maud 1980). They occur at unpredictable intervals, however, rather on a basis of decades (Grundling, 2014; Neumann et al., 2010). These extreme weather events seem to be important for the replenishment of coastal aquifers (Kelbe et al., 1995), as well as for maintenance of the seed banks of aquatic plants in peatlands and semiaquatic plants in temporal wetlands (pers. comm. L Pretorius).

Described as the Maputaland Coastal Belt, the vegetation consists of fire-climax grasslands and coastal forests. Moreover, the study area is rich in biodiversity and endemism, represented by azonal features such as swamp forests, mangrove forests, subtropical dune thickets, freshwater wetlands and other environments (Mucina and Rutherford, 2006).

The Kosi Bay lake system has an easterly confinement of a high coastal barrier dune cordon which is breached at the Kosi Mouth (an estuary with tidal flats). Behind the estuary lies a system of four lakes, of which the largest one (Lake Nhlange) is 35 km² in size. All four lakes are connected by small channels (Cooper et al., 2012). Only 5% of the lake water originates from the freshwater influx of a river into the fourth lake; whereas 95% is a result of the high water table, permitted by the high porosity of the surrounding coarse sandy substrates (Begg, 1980; Wright et al., 2000).

Geologically, the aeolian-sourced coastal dune cordon is the youngest element (9000 years) (Cooper et al., 2012; Maud, 1980). Behind the cordon lies an undulating dune landscape covered by a stratum of unconsolidated medium to coarse grained sand. During the last glacial cycle it was periodically (re-) mobilized and wind-distributed, before it became fixed by vegetation in the early Holocene (Botha and Porat, 2007; Grundling, 2014; Maud, 1980).

The underlying stratum at a depth of 10-20 m is the Kosi Bay Formation, which consists of sandy silts with moderate contents of clay (Grundling, 2014). The occurrence of wetlands and peatlands is associated with this Kosi Bay formation, as the near-surface water table is perched due to clay content of the substrate (Botha and Porat, 2007).

Based on the South African concept of hydrogeomorphic wetland types (Ollis et al., 2013), one finds on the lower Maputaland Coastal Plain four dominant wetland types; namely channelled valley-bottoms, unchannelled valley-bottoms, depressions, and seeps (Grundling, 2014). The first three are the main peat accumulating types (M. Gabriel, 2014, personal observation).In comparison with the depression peatlands, the characteristics of the two valley-bottom peatland types are quite similar. Two sites were chosen in this study to represent valley-bottoms and depressions. Because of the geological setting and consistency with other literature, we will from now on refer to depressions as interdune depressions (Faul et al., 2016; Grundling, 2014; Pretorius, 2011).

The first peatland studied is 38,1 ha large and lies in a small valley named Matitimani. The study site (site VB) is located at 11 m.a.s.l. at 26°57'20.97"S; 32°49'0.36"E. It is approximately 2 km long and meets Lake Nhlange at its southern end. It was investigated before and is known for deep peat layers including wood peat (Faul et al., 2016; Grundling et al. 1998; Moning, 2004;). During the fieldwork (March 2014) the vegetation at the coring site was composed of *Typha capensis, Thelypteris interrupta, Pycreus nitidus, Cyperus prolifer* and *Cyperus sphaerospermus*, in order of dominance. However, aerial photographs from past decades show that until recently the natural vegetation was composed of peat swamp forest. The peat swamp forest was cut on a section of about 500 m between 1990 and 1996 (Figure 2.1(c)), to establish vegetable gardens - clearly evident by burnt tree stumps, inactive drainage ditches and solitary banana plants (*Musa x paradisica*).

The second study site (site ID) is small peatland named KwaMazambane, at 21 m.a.s.l. and 26°56'52.62"S; 32°48'54.15"E. It lies about 900 m north of the first study site, in a rather flat area just above the head of the Matitimani valley. It is a small depression of 0,3 ha. The peatland hosts *Eleocharis dulcis* and *Cyperus sensilis* as dominant species; *Pycreus polystachyos* and *Thelypteris interrupta* are common. Cultivation is practised on artificially elevated beds on the margins of the wetland. The inner part seems pristine, which makes the site reliable for palaeoecological investigations.

2.3 Methodology

The two peatlands were each investigated along a transect of soil cores, creating a detailed stratigraphy of the substrates between the soil surface and the valley-bottom sand. At site VB the distance between the corings was about 15 m, and at the much smaller site ID, the distance between the corings was about 7,5 m. Every core was examined by means of a standardised soil profile description. As a basis for the description the *German pedological mapping directive KA 5* (Ad-hoc-AG Boden, 2005) was used, as it allows peatland substrates to be distinguished by their accumulation processes and botanical composition, as well as soil forming processes. A detailed morphological description is given in supplementary material 1. The degree of peat decomposition was determined for peat substrates according to the Von Post Humification Scale (von Post, 1922). Subsequently, one point within each transect was chosen for the macrofossil analysis. These points were selected from the deepest sections of the peatlands, at the sites with the most comprehensive stratigraphies. Three volumetric samples were taken from each horizon and dried at 105°C to determine the dry bulk density (DIN EN 15934, 2012).

Sediments were taken with a Russian peat corer with a 500 mm length and a 52 mm width. The extracted cores were packed in plastic tubes and plastic foil, and stored in a fridge at 5°C. The total length of core VB is 4,59 m and of core ID, 1,5 m. Each core was later cut into sections of 10 mm thickness and subsequently wet-sieved (200 µm). A one centimetre broad vertical section was left at the side of the core and cut into 50 mm long sections. These were used to determine the organic matter content using the Loss on Ignition method at 550°C (Schulte and Hopkins, 1996). The plant macrofossils were examined under a stereomicroscope, and carpological findings (seeds, fruits), charcoal pieces > 1mm, pieces of insects and wood, were collected and counted. The identification of seeds and fruits was done by optical comparison with a self-compiled carpological collection from recent local wetland plants. Further, literature containing photographs and images of seeds was used for the identification of plant macrofossils, e.g. Gordon-Gray (1995) and Cook (2004). Wood identification was done by comparison with living and dead trees of different species, according to fibre characteristics. The ecological requirements of several species were used to distinguish wet and dry phases in the peatland development. As an indication of inundation *Nymphaea* sp. and *Utricularia* sp. (Cook, 2004) were used; for shallow inundation *Eleocharis dulcis* and *Schoenoplectus corymbosus* var. *brachyceras* (Cook, 2004); for seasonal dryness *Cyperus sensilis* and *Cyperus prolifer* (Baijnath, 1976; Cook 2004); and for non-obligate wetland plants *Pycreus polystachyos* and *Centella asiatica* (Cook, 2004; Pretorius, 2012).

At each site one well was installed inside the peatland and another just outside at the peatland's fringe (Figure 2-2). Water tables were measured in the wells after every dry and wet season. Rainfall was measured daily with a rain gauge in the town of eManguzi, which is located 10 km from the research sites.

Nine radiocarbon dates were analysed with accelerator mass spectrometry (AMS) in the Max Planck Institut für Biogeochemie in Jena, Germany. For this purpose, plant macrofossils were collected from the sediments sequences, converted into solid graphite, and measured with accelerator mass spectrometry (AMS). The age depth models were calculated using the software OxCal v.4.2.4 (Bronk Ramsey, 2009), calibrating along the SHCal13 atmospheric curve (Hogg et al., 2013). The age-depth models were calculated using the *P_Sequence* function (k_0 parameter = 1 cm^{-1}; interpolation: 0.5-cm resolution, $log_{10}(k/k_0)$ = 1. The most distinct changes in the sediment composition, which might be a signal of changes in the peat accumulation rate, were introduced to the models using the Boundary command. The mean value of the modelled age was selected as reflecting the modelled age, which is expressed as cal yr BP (years before AD 1950).

Radiocarbon ages of the publication Ramsay (1995) were recalibrated with SHCal13, to make them comparable. A table with post and past conversion dates can be found in supplementary material 2. Three standard accumulation rates were calculated. The vertical accumulation rate (VAR) was calculated according to the C14-dates and the upper and lower depth with equation (1).

$$VAR = \frac{E}{Age_{\_ll} - Age_{\_ul}} \tag{1}$$

E= vertical extent of a layer; $Age_{\_ll}$ = age of lower layer limit; $Age_{\_ul}$ = age of upper layer limit.

By selecting certain sections with homogenous peatland development, carbon accumulation rates (CAR) of individual substrates per m² and year were calculated with equation (2).

$$CAR = \frac{E \times 10000 \times BD \times C}{Age_{\_ll} - Age\_ul} \tag{2}$$

BD=bulk density of dry mass; C= carbon content [g carbon / g soil].

A conventional way of describing peat accumulation rates is the long-term apparent rate of carbon accumulation (LORCA) (Clymo et al, 1998). This value refers to the average amount of carbon which is annually stored in a peatland and is calculated with equation (3).

$$Lorca = \frac{M_T}{T} \tag{3}$$

M_T=cumulative dry mass of carbon of each layer, as calculated with equation (4).

$$M_T = \sum_i^n (E_i \times BD_i \times C_i \times 10000) \tag{4}$$

i = index for layer

2.4 Results

2.4.1 Peatland substrates and stratigraphies

Substrate qualities are compiled in Table 2-1 and Table 2-2 which supply information on the calculated ages of the section limits, values for the degree of peat decomposition, organic matter content and bulk density, together with a verbal description of the macroscopic features.

2.4.2 Macrofossil records and peatland development phases

2.4.2.1 SITE VB

In total, 24 carpological findings could be identified, most of them at species level. Three wood types could be identified as well. According to the occurrences and frequencies of carpological findings of aquatic, semiaquatic and terrestrial plants, as well as by the amounts of charcoal, wood fibres and the content of organic matter, eight distinct phases of peatland development were distinguished (Figure 2-3). Three unidentified seeds, which are abundant in distinct sections, are considered in the compilation as well.

VB-1 (4,59-4,69 m; 6260-6159 cal yr BP): The substrate consists of sand gyttja, which was underlain by yellow-whitish valley-bottom sand. No undisturbed section for macrofossil examination or dating could be obtained.

VB-2 (4,59-3,27 m; 6159-5292 cal yr BP): The substrate consists of organic gyttja with a high proportion of sand and some rootlets. Aquatic plant seeds (.e.g. *Nymphaea* sp., *Utricularia* sp.) were found with great frequency; also algae oospores (*Chara* sp. and *Nitella* sp.). Further, seeds from semiaquatic vegetation such as *Eleocharis dulcis* are found as well, in association with seed from terrestrial vegetation such as *Pycreus polystachyos*. The organic matter increases between 3,9 m and 3,27 m from 26 to 76% due to the ingrowth of roots from the later formed open sedge- mire of the layer above. Another sharp increase of organic matter is evident between 4,1-4,0 m.

VB-3 (3,27-2,18 m; 5292-2479 cal yr BP): At a depth of 3,27 m a shift from gyttja to peat is observed. Up to 3 m, flattened stem bases of sedges were frequently encountered; later, small rootlets were the principal component of the substrate, indicating a shift to an open sedge mire. This shift to drier conditions is strikingly evident in the macrofossil record by a sudden lack of aquatic species, like *Nymphaea* sp. and *Nitella* sp., as well as the semiaquatic *Eleocharis dulcis*. The saw-sedge *Cladium mariscus* subsp. *jamaicense* gains dominance, together with *Cyperus* sp., accompanied by *Hydrocotyle bonariensis*, *Persicaria amphibia, Dissotis canescens.* The peat has a medium to high degree of decomposition. In contrast to the prior stage, where charcoal was always found in small quantities, there is a distinct increase in severe fire events in this stage, evident by the high concentrations of macrocharcoal in the macrofossil record.

Table 2-1: Detailed description of substrates at site Valley-Bottom. DD=degree of decomposition; OM=organic matter; BD=bulk density.

Site Valley-Bottom						
Section	**Depth [m]**	**Age [cal yr BP]**	**DD**	**Ø OM [%]**	**BD [g/cm³]**	**Substrate**
VB-8	0-0.12	2014 AD-64	H4-H5	86.2	-	**Amorphous peat – radicell peat:** This layer presents a peat-building horizon within a layer of decomposed peat. Many recent (but dead) radicells are building a new peat layer. They derive from the succession community which followed the cultivation.
VB-7	0.12-0.58	64-416	H5-H8 increasing downwards	92.7	0.13	**Amorphous peat – radicell peat:** The substrate consists of radicell peat from the sedge-dominated succession vegetation within a matrix of amorphous peat. With increasing depth the radicells decrease and the amorphous fraction increases.
VB-6	0.58-1.72	416-1206	H3-H5	95.0	0.09	**Wood-peat** with high content of *Syzygium cordatum* and *Ficus trichopoda*. The general matrix was higher decomposed wood-peat and dark brown radicells from woody plants.
VB-5	1.72-2.05	1206-2135	H7-H8	86.5	0.14	**Radicell peat**
VB-4	2.05-2.18	2135-2479	H9-H10	84.0	-	**Peat-Gyttja**
VB-3	2.18-3.27	2479-4946	H5-H8	86.7	0.14	**Radicell peat - coarse sedge peat:** The lower 25 cm of this layer consist of coarse sedge peat. In the upper part the substrate consists of radicell peat.
VB-2	3.27-4.59	4946-6159	-	3.3 m: 75.5 4.5 m: 30.6 mean: 44.7	3.3 m: 0.28 4.5 m: 0.38 mean: 0.33	**Organic gyttja** with some residues of radicells, stout vertical sedge-roots and weakly decomposed tree roots. Sand gyttja between 390 to 400 cm. This is due to a slighty increased input of sand, and it drops the OM to slightly below the classificatory limit of 30%.
VB-1	4.59-4.69	-	-	-	-	**Sand gyttja**

Table 2-2: Detailed description of substrates at site Interdune Depression. DD=degree of decomposition; OM=organic matter; BD=bulk density.

Site Interdune Depression						
Section	**Depth [m]**	**Age [cal yr BP]**	**DD**	**Ø OM [%]**	**BD [g/cm³]**	**Substrate**
ID-6	0-0.14	2014 AD-91	H6	76.1	0.09	**Radicell peat** with minor content of gyttja. The gyttja, however, increases the outcome of the von Post test (von Post, 1922), whereas the radicells are actually in a less decomposed stage (H2-H4).
ID-5	0.14-0.27	91-170	H5-H6	80.6	0.15	**Peat-Gyttja** with plenty of radicells from the recent vegetation. In the field description considered as radicell peat. Because of the seed-record rectified as Peat-Gyttja.
ID-4	0.27-0.42	170-263	H9	61.2	0.16	**Peat-Gyttja** with the quantity of radicells and gyttja roughly equal.
ID-3	0.42-0.80	263-485	-	34.8	0.27	**Organic gyttja** with minor quantities of sedge radicells.
ID-2	0.80-1.05	485-648	-	28.6	0.34	**Sand gyttja** rich in organic matter. Radicells are still frequent.
ID-1	1.05-1.60	648-861* *(in 1,5 m)	-	24.1	0.56	**Sand gyttja** rich in organic matter. Very few radicells.

VB-4 (2,18-2,05 m; 2479-2135 cal yr BP): This layer consists of organic gyttja intermixed with rootlets. The macrofossil record gives evidence of another period of inundation at the site, visible by the amount of *Nymphaea sp.* seeds. The dominance of *C. mariscus* subsp. *jamaicense* and *Cyperus* sp. ends here.

VB-5 (2,05-1,72 m; 2135-1206 cal yr BP): The substrate consists mostly of rootlets and has varying degree of decomposition between H6 and H8. In the macrofossil record seeds are rare. In 1,79-1,76 m oospores from aquatic *Nitella* sp. are abundant.

VB-6 (1,72-0,58 m; 1206-416 cal yr BP): Wood becomes the dominant peat builder with most frequent occurrences of the waterberry (*Syzygium cordatum*) and the swamp fig (*Ficus trichopoda*). A high percentage (up to 40% of the bulk) of unidentified leaves was found at 1,4-1,33 m. Seeds of herbaceous vegetation are few in number. The absence of charcoal merely indicates that fire was very seldom able to penetrate into the peat swamp forest. The preservation of the peat is excellent with a degree of decomposition between H3 and H5. This is also visible in the high amount of organic matter with average 95%.

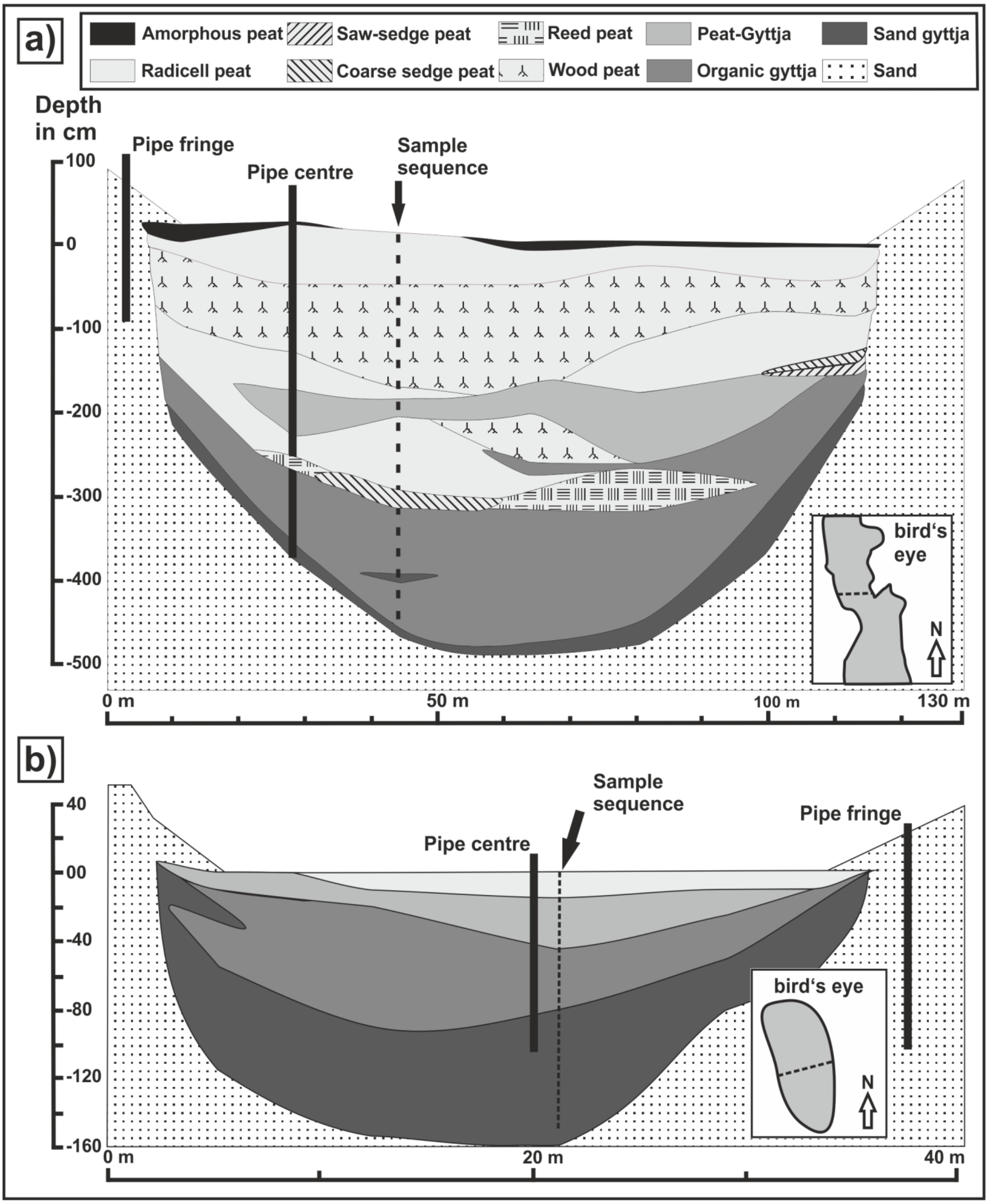

Figure 2-2: Detailed stratigraphies of **(a)** site VB and **(b)** site ID. The vertical 0 cm is at the peatlands' lowest point. In pipe fringe and pipe centre, water tables were measured (Figure 2-5). The cross section goes from west (left) to east (right). The small image shows the transect (dashed line) within the peatland from a bird's eye view.

VB-7 (0,58-0,12 m; 416-64 cal yr BP): In this section the substrate consists of radicell peat within a layer of amorphous peat. The clearing of the peat swamp forest in the early 1990s and the implementation of drainage channels resulted in the decomposition of the uppermost peat layer. The macrofossil record points out that the initial peat must have consisted of wood-peat, as it shows the typical lack of sedges and aquatic species. Instead, same as in VB-6 seed *unknown 3* occurs, which probably belongs to a tree or shrub. The decomposition ranges between H5 and H8, decreasing downwards with a diminishing presence of radicells. The average content of organic matter is due to the decomposition slightly lower than for the preserved wood peat, 92,7 % vs. 95,0. The lack of charcoal below 0,2 m suggests that no anthropogenic turbation of the soil took place, as fire is nowadays almost an annual feature, especially related to cultivation practices.

VB-8 (0,12-0 m; 64 cal yr BP – 2014 AD): The uppermost layer is the one most affected by human activities. It also consists of radicell peat formed in amorphous peat; however, the quantity of rootlets is higher. This is also indicated by the lower degree of decomposition. The macrofossil record indicates that at the start of the disturbance various species were part of the succession vegetation, dominated by Cyperaceae like *Pycreus nitidus*, *Pycreus polystachyos*, *Fuirena umbellata* and *Cyperus* sp., as well as by *Typha capensis*. An increased number of unidentified carpological findings indicates that this layer is influenced by new in-moving species. Macrocharcoal pieces are frequent. A drop in the content of organic matter indicates that this upper part of the soil was stronger affected by mineralisation than the substrate of VB-7.

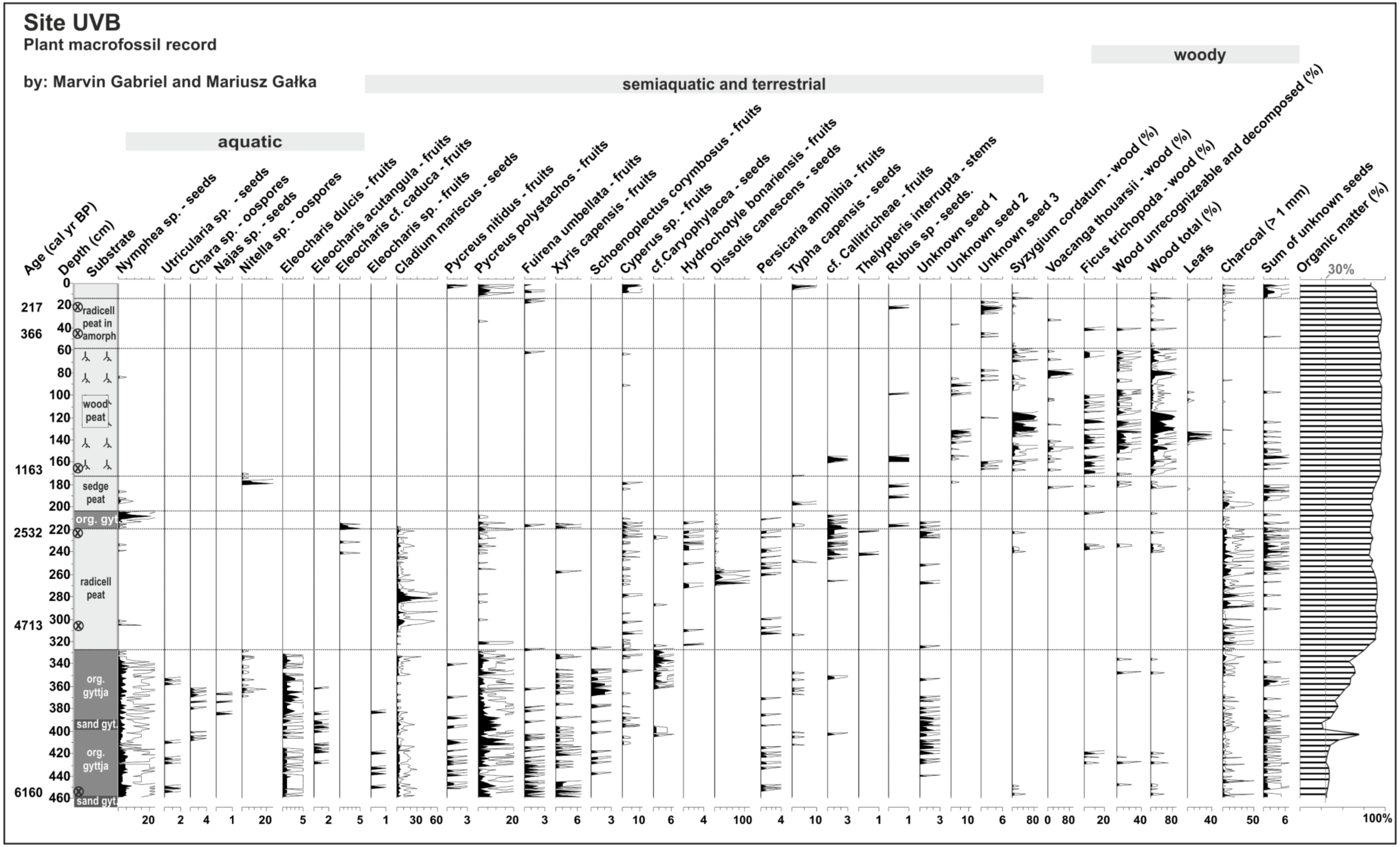

Figure 2-3: Macrofossil record of site VB. The depth is indicated on the y-axis. On the x-axis are the macrofossils of each species (names are given above) counted in numbers, except for the quantities of wood, leafs and organic matter which are given in percentage. Exact numbers are depicted in black area; the slim line is a five-times exaggeration for better visualisation.

2.4.2.2 SITE ID

In total 20 carpological findings could be identified, most of them at species level. According to the occurrences and frequencies of carpological findings of aquatic, semiaquatic and terrestrial plants, as well as by the amounts of charcoal and the content of organic matter, six distinct phases of peatland development were distinguished (Figure 2-4). Nine frequent unidentified seeds are also included in the compilation.

ID-1 (1,60-1,05 m; 920-648 cal yr BP): The substrate from the deepest part of the peatland consists of sand gyttja with a considerable proportion of organic matter. Sand gyttja is a lake sediment, that may also form in shallow water (Ad hoc AG Boden 2005). Therefore, the aquatic *Nymphaea* sp. and the semiaquatic *Eleocharis dulcis* appear in the record as dominant species, accompanied by *Xyris capensis* and unknown seed 1, which probably prefers inundation. However, terrestrial species like *Pycreus polystachyos* also occur regularly, indicating water-level fluctuations.

ID-2 and ID-3 (1,05-0,42 m; 648-263 cal yr BP): A slight change which favoured drier vegetation took place in this period. *Nymphaea* sp. and *Eleocharis dulcis* are still abundant, but other plants such as *Cyperus* sp. and *Rhynchospora holoschoenoides* gain importance as well. Also the slight increase of charcoal indicates drier conditions. Other aquatics such as *Nitella* sp., *Potamogeton* sp. and *Utricularia* sp. appear sporadically, indicating periods of inundation. The content of organic matter increases slightly upwards, with the 30% mark defining the border between sand gyttja and organic gyttja. Generally speaking the lower part, to a height of 0,8 m is classified as sand gyttja and the part above this as organic gyttja.

ID-4 (0,42-0,27 m; 263-170 cal yr BP): The increase of rootlets in this section leads to the classification of the substrate as peat gyttja. An increase of fruits from *Cyperus* sp. and *Fuirena obcordata*, as well as insect pieces, indicate another shift to slightly drier conditions. The content of organic matter increases upwards, which is caused by the ingrowth of radicells from overhead.

ID-5 (0,27-0,14 m; 170-91 cal yr BP): The substrate in this section is marked by a high number of aquatic seeds and a lack of terrestrial plant seeds. Furthermore, a decrease in charcoal is observed together with the presence of eggs of the water flea *Daphnia* sp. Although it appears from the macrofossil record that the substrate was accumulated throughout inundation (as organic gyttja), there is a bulk of radicells which penetrated the layer afterwards from above.

ID-6 (0,14-0 m; 91 cal yr BP – 2014 AD): The substrate of the uppermost layer consists of radicell peat with intermixtures of organic gyttja. The radicells are mostly from *Cyperus sensilis*, accompanied by dark and ridged rootlets from *Thelypteris interrupta.* These are somewhat decomposed and entangled with living ones. Even though these radicells visually appear to be in a state of low decomposition, the von Post squeezing test yields a degree of H6 (one third of the sample is pressed out of the hand), due to the intermixtures of organic gyttja.

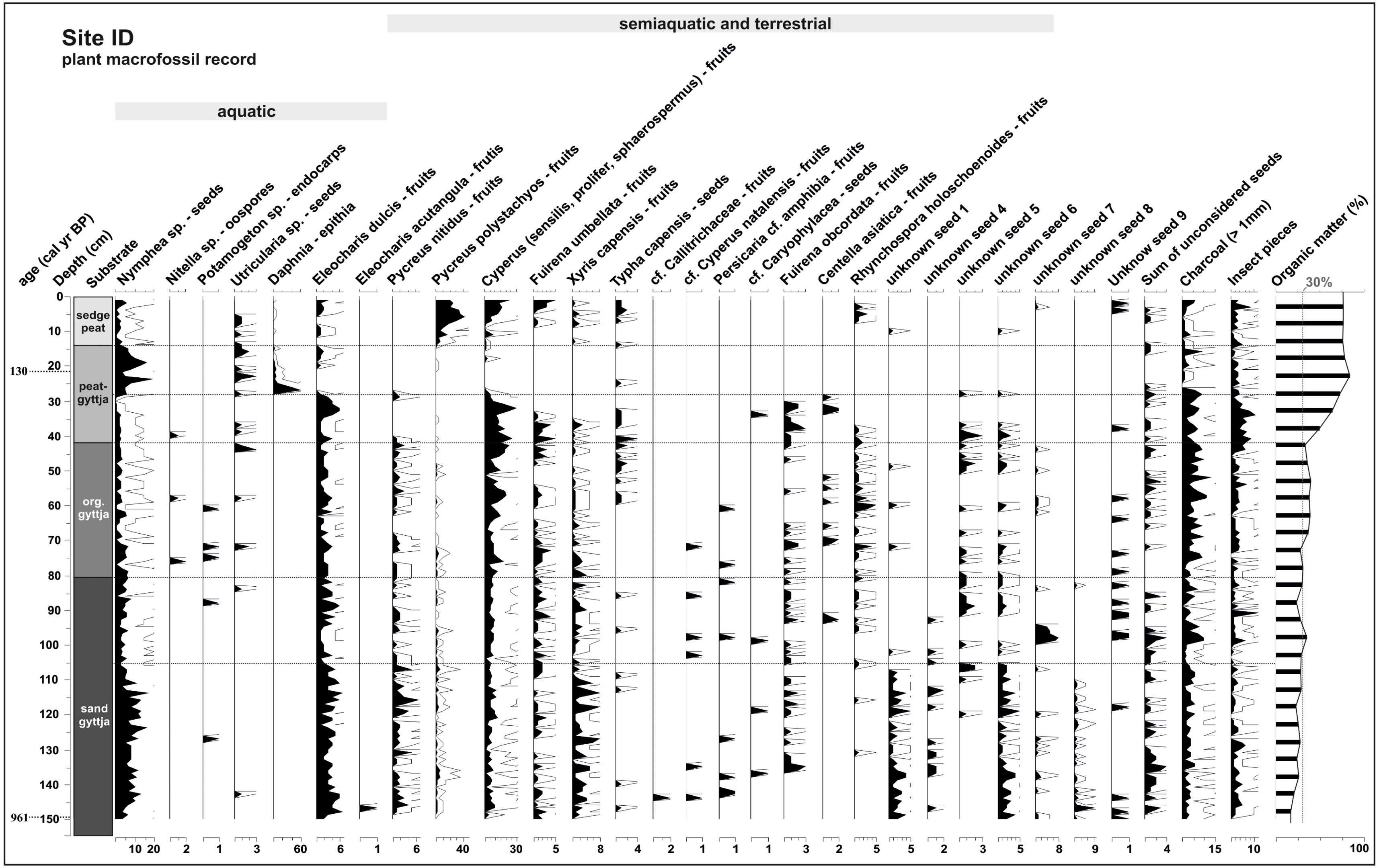

Figure 2-4: Macrofossil record of site ID. The depth is indicated on the y-axis. On the x-axis are the macrofossils of each species (names are given above) counted in numbers, except for the quantity of organic matter which are given in percentage. Exact numbers are depicted in black area; the slim line is a five-times exaggeration for better visualisation.

2.4.3 Water tables

The water levels of the peatlands at different seasonal stages are depicted in Figure 2-5. The surface heights of the fringe points are higher than the peatland surface and the differences were therefore adjusted to the same reference level. In the case of site ID this was 0,42 m, and in the case of site VB, 0,61 m.

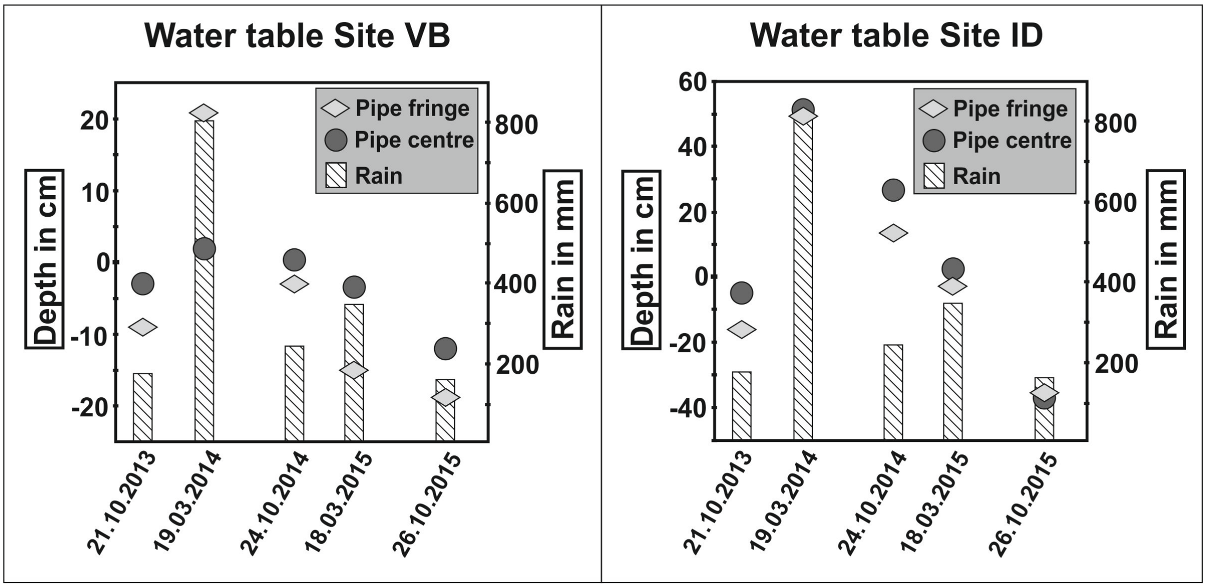

Figure 2-5: Two years of water table measurements in wells, measured at a frequency of about half a year. On the left y-axis, 0 marks the peatlands' surface where the central pipe was installed. The right y-axis depicts the measured sum of precipitation from one date to the other (the first from 18 March 2013 to 21 October 2013).

2.4.4 Radiocarbon dates and age-depth model

The results of the radiocarbon analysis are given in Figure 2-6(a). Figure 2-6(b) shows the age-depth models for the two sites.

a)

Depth cm	Dated Material	Nr. Lab.	F14C	Er. F14C	cal yr BP σ=95,4%			cal yr BP σ=68,2 %		
Site VB					From	To	Mean	From	To	Mean
21-22	2 unknown seeds	12587	0,974	0,0024	292	142	**217**	225	143	**184**
44-45	1 seed (unknown seed 3)	13334	0,962	0,0033	446	285	**366**	438	296	**367**
165-166	1 seed (unknown seed 3)	12585	0,854	0,0024	1260	1066	**1163**	1185	1064	**1125**
220-221	5 Cladium seeds	13335	0,736	0,0035	2715	2349	**2532**	2543	2349	**2446**
304-306	6 Cladium seeds	12584	0,591	0,002	4840	4586	**4713**	4769	4610	**4690**
393-394	7 Cladium seeds	12583	0,496	0,002	6439	6298	**6369**	6400	6319	**6360**
455-459	3 Cladium seeds; 1 Eleocharis caduca seed; 2 Eleocharis dulcis pieces	13333	0,507	0,0023	6304	6027	**6166**	6304	6177	**6241**
456-457	2 pieces of charcoal	13336	0,508	0,0018	6291	6026	**6159**	6291	6176	**6234**
Site ID										
21-22	4 Eleocharis dulcis seeds	12589	0,982	0,0024	259	0	**130**	146	0	**73**
149-150	2 1/2 pieces Eleocharis dulcis seeds + pieces	12588	0,883	0,0023	922	800	**861**	916	810	**863**

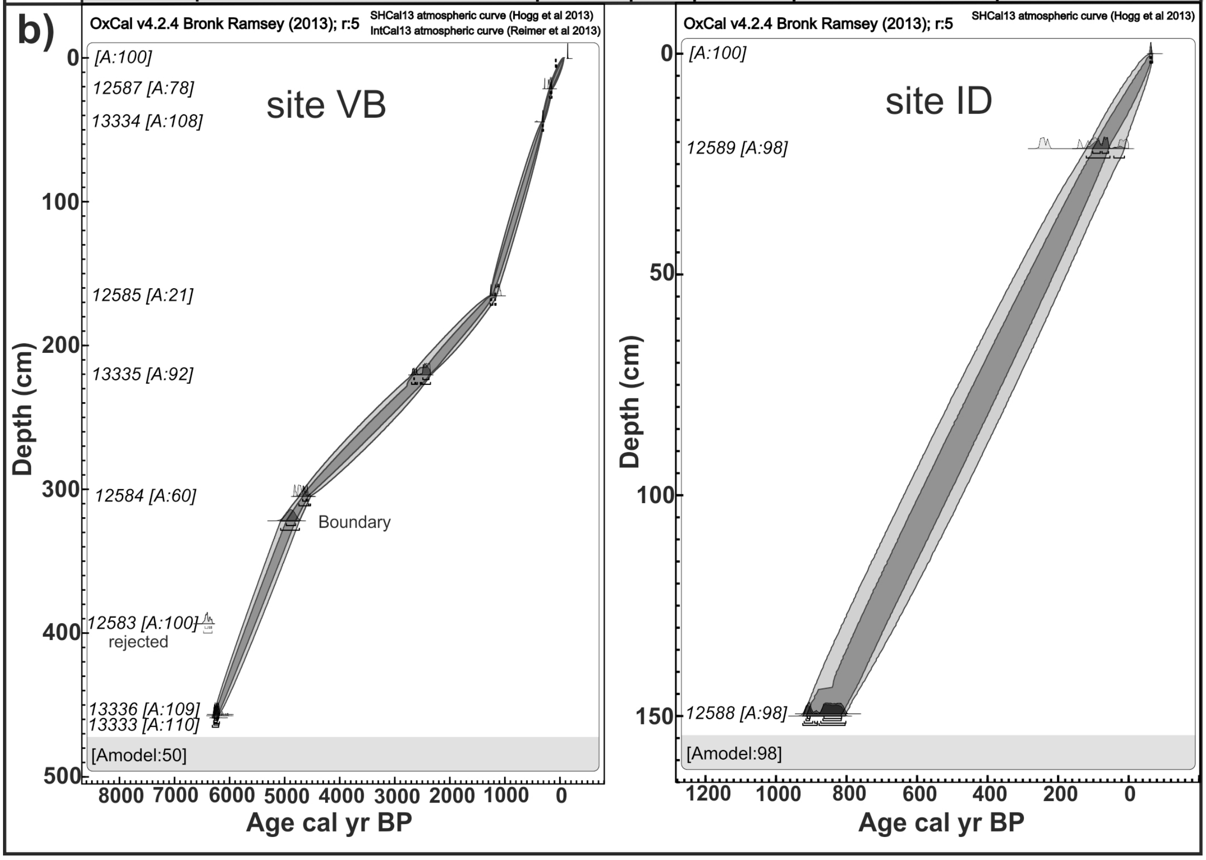

Figure 2-6: Radiocarbon dates: **(a)** results of radiocarbon dating – sample marked in grey is thought to be flawed and was disregarded for the preparation of the age–depth model; **(b)** age–depth models.

2.4.5 Accumulation rates

Accumulation rates were calculated in three ways: firstly in mm per year (Table 2-3(a)), secondly in carbon per m² and year for selected substrates (Table 2-3(b)), and thirdly in long-term apparent rate of carbon accumulation (LORCA) for each peatland (Table 2-3(c)).

Table 2-3: (a) Vertical accumulation rates in between the radiocarbon dated depths. Above, site VB, below site ID. Time refers to the radiocarbon dates (68.2% probability) with 2014 as the t=0; **(b)** accumulation rates in mm/year and annual carbon accumulation for selected substrates; **(c)** LORCA values for site VB and site ID.

a) vertical accumulation rates for the sections in between radiocarbon dates

Depth [mm]			**Time [yr]**			**Accumulation Rate [mm/yr]**	**Dominant Substrate**
From	**to**	**dt**	**From**	**to**	**dt**		
Site VB							
0	215	215	0	248	248	0,94	decomposed wood peat + radicell peat
215	455	240	248	431	183	1,31	slightly decomposed wood peat
455	1655	1200	431	1227	796	1,51	wood peat
1655	2205	550	1227	2510	1283	0,43	organic gyttja + radicell + wood peat
2205	3050	845	2510	4754	2244	0,38	Radicell peat
3050	4575	1525	4754	6298	1544	0,99	organic gyttja + coarse sedge peat
0	**4590**	**4590**	**0**	**6298**	**6298**	**0,73**	**over all substrates**
Site ID							
0	215	215	0	137	137	1,57	radicell peat
215	1500	1285	137	927	788	1,63	organic gyttja & sand gyttja
0	**1500**	**1500**	**0**	**927**	**927**	**1,62**	**over all substrates**

b) carbon accumulation rates according to substrate

Substrate	**Accumulation rate [mm]**	**Bulk density [g/cm^3]**	**Accumulated weight [g]**	**Corg* [g/g dry mass]**	**C-accumulation [g/(m^2*yr)]**
wood peat (VB-6)	1,5	0,11	166	0,55	**91**
radicell peat (VB-3)	0,4	0,14	53	0,50	**26**
organic gyttja (VB-2)	1,0	0,33	338	0,22	**76**
radicell peat (ID-5 - ID-6)	1,6	0,09	141	0,44	**62**
sand- & organic- & peat-	1,6	0,33	538	0,19	**102**

C) LORCA

Site	**MT [g]**	**Base date [cal yr BP]**	**LORCA [gC/m^{2}yr]**	* the carbon content was calculated with a SOM/SOC ratio of 1,73 (Klingenfuß et al., 2014)
Site VB**	340671	6220	**55**	** missing bulk densities were estimated for the calculation as: B-4=0,2 g/cm^3 and VB-8=0,17 g/cm^3
Site ID	82320	925	**89**	

2.5 Discussion

2.5.1 Substrate composition and formation in relation to vegetation type

The encountered substrates can be divided into three major divisions: Peat, gyttja and peat gyttja, and mineral fraction.

2.5.1.1 PEAT

Three main peat types were encountered: *wood peat*, *radicell peat* and *coarse sedge peat*. *Wood peat* is a product of peat swamp forests, the common vegetation type in valley-bottom peatlands such as at Matitimani (site VB) (Grobler, 2009). We identified *Syzygium cordatum, Ficus trichopoda* and *Voacanga thouarsii* as the main peat building species of this vegetation community. Why this vegetation type is not occurring also on interdune depressions is unclear. Venter (2003) states a hypothesis that the occurrence of peat swamp forests may be related to groundwater movement and -qualities, as they occur in areas with high groundwater seepage. This statement coincides with findings of a hydro-ecological study by Taylor et al. (2006) at the eastern shore of Lake St. Lucia. Here, swamp forest was encountered in saturated seepage areas.

At site ID an active *radicell peat* building plant community is present, with *Cyperus sensilis, Eleocharis dulcis* and *Pycreus polystachyos*. The latter has a very dense rooting system which emphasises an important role during radicell peat accumulation.

At site VB the period of proper *radicell peat* accumulation was VB-3, with different *Cyperus* species. and *Cladium mariscus* subsp. *jamaicense* as the most important carpological species. The *Cyperus* species probably account for the bulk of the fossil rootlets. Unfortunately, most of their small fruits were damaged during the sieving process, but the sizes correspond with those of *C. prolifer* and *C. sphaerospermus* from the current vegetation.

Coarse sedge peat, as found in the lowest 0,25 m of VB-3, supposedly forms from stem bases from the Cyperaceae, during periods of shallow inundation. In site VB it marks the transition between the infilling of the water body with gyttja (terrestrialisation) and secondary mire formation by the accumulation of radicell peat. According to the carpological findings, the genus *Cyperus* formed the dominant vegetation during that time.

The saw-sedge *Cladium mariscus* subsp. *jamaicense* might also have contributed to the fossil rootlets; however, no typical saw-sedge peat was formed. Saw-sedge peat was found only in the eastern part of the site VB cross section (Figure 2-2 (a)), in the first period of the secondary mire formation on top of the terrestrialisation stage. Assumingly this substrate only forms under conditions where stem bases are inundated. However, the peat-forming ability of *Cladium mariscus* subsp. *jamaicense* in South Africa requires additional palaeobotanical studies. Also in the case of the European species *Cladium mariscus* this issue is still debated (Gałka and Tobolski 2011, 2012).

2.5.1.2 GYTTJA AND PEAT-GYTTJA

Gyttja is known as a typical substrate forming during the initial terrestrialisation process – the infilling of a lake body (Succow and Joosten, 2001). The organic components of gyttja consist of limnic sedimented dead organic particles (detritus) from plants or animals in different stages of decomposition (Succow and Joosten, 2001). In our study gyttja is found at both sites, with *organic gyttja* at site VB and mostly *sand gyttja* at site ID. According to the macrofossil record, *Nymphaea* sp. presumably accounts for the bulk of the organic matter, next to other aquatic species which occur sporadically (e.g. *Utricularia* sp. and *Nitella* sp.). The results further indicate *Eleocharis dulcis* as an important plant for gyttja formation as well. Under alternating hydrological conditions *Pycreus polystachyos* seems to be important as well. This may either disprove its indicator value as dry species (Cook, 2004), or emphasise the seasonal intensities of dry periods in dominantly terrestrialising peatland systems like VB-2.

When water levels fluctuate consistently between surface and inundation, a substrate is formed, which contains about equal quantities of peat and gyttja. In the *German Pedological Mapping*

Directive KA5 (Ad-hoc-AG Boden 2005) such a substrate is not recognised. According to its characteristics we address it as *peat-gyttja*. The macrofossil record of section ID-4 reveals both inundation (*Nymphaea* sp., *Eleocharis dulcis*) and drier intervals (*Cyperus* sp., insect pieces). Even in the actual peat-forming layer ID-6 a considerable amount of gyttja is present, although the bulk body consists of radicells. A look at an automatic rainfall station in Kosi Bay reveals high annual precipitation variations. From 1989 to 2003 a mean of 894 mm was recorded with a standard deviation of 420 mm. The highest precipitation of 1913 mm was received in 2000 (most of it during cyclone Eline); the lowest in 1998 of 401 mm (ARC-ISCW, 2011). As a consequence of these extreme years, periods of dryness or inundation prevail for one or two years until an average hydrologic state is established again. These periods are time windows for the development of different moisture-related vegetation communities. Interdune depression peatlands, such as site ID, where water cannot drain immediately, are strongly influenced by these pronounced hydroperiods. During inundation organic gyttja accumulates, and during non-inundated periods radicell peat accumulates. Hence, interdune depressions are the main forming environments for peat-gyttja.

2.5.1.3 MINERAL FRACTION

The mineral fraction of the substrates is virtually completely made of medium grained sand. Even though the surrounding dunes are vegetated, the existence of sand within peat deposits indicates that transport processes take place. It could be expected that fire events play in important role for the mobilisation of sand, due to the burning of the vegetation cover. Usually medium grained sand is transported by the wind over short distances in the air (Blume et al., 2010). Thus, a higher mineral content is found in site ID which has a short distance to the source of sand in the surrounding dunes. The highest organic matter concentration in peat was encountered is the undecomposed wood peat of VB-6 with a mean of 95%. Clearly the rather horizontal aeolian transport of sand does not enter the central part of a dense peat swamp forest.

2.5.2 Landscape hydrological setting

A notable difference between the two examined peatlands is the amplitude of the (seasonal) water table fluctuations (Figure 2-5). A fluctuation of 88 cm was noticed during the measuring period at site ID, but only 14 cm at site VB. According to Botha and Porat (2007) the wetlands around the Kosi Bay lake system receive their water from the perched water table of the clay-rich Kosi Bay Formation, which lies near to the surface in that area. Grundling (2014) refers to this water source as the shallow Maputaland aquifer. Hence, both study sites are flow-through systems - site ID however, is situated in a higher position in the Matitimani catchment; and site VB in a lower position. The higher position makes site ID more susceptible to the fluctuating hydroperiods, whereas site VB in a lower position receives a more constant water flux. A second reason for the difference in the amplitude lies in the geomorphic setting. The water level in site ID corresponds to the water level of the surrounding rather flat area, and when the water level is higher than the peatlands surface inundation occurs in the interdune depression. In site VB on the contrary, inundation doesn’t occur due to the open-ended valley shape and the slightly inclined nature of a valley. High rainfall in March 2014 (370 mm measured in eManguzi) raised the groundwater level around site ID, leaving it inundated for many months (Figure 2-5). At site VB this severe weather event resulted merely in some diffuse surface runoff towards Lake Nhlange, lasting a few days (M. Gabriel, 2014, personal observation).

2.5.3 Accumulation rates

Site ID has a vertical accumulation rate (VAR) of 1,62 mm/yr and site VB of 0,73 mm/yr. These findings match with the results of Grundling et al. (1998) who calculated an average VAR=1,06 mm/yr for eight peatlands of northern Maputaland, however with a much larger span between 0,28mm/yr and 6,54 mm/yr. The last value might be an overestimation due to the dating of penetrating root material. The long-term apparent rate of carbon accumulation (LORCA) is 89 $gCm^{-2}yr^{-1}$ for site ID and 55 $gCm^{-2}yr^{-1}$ for site VB. The difference between the two study sites can be explained by three factors: the degradation of site VB, the different peatland's ages, and the hydrological conditions. An intact peatland can be divided into the *acrotelm* (peat producing layer) and the *catotelm* (peat storing layer) where the partly decomposed material finally becomes isolated from aerobic decomposition (Succow and Joosten, 2001). Accumulation rates derived for the *acrotelm* are usually higher (Joosten and Clarke, 2002). Site VB, whose uppermost 0,58 m are affected by drainage, has a disturbed acrotelm and therefore lower topsoil values. Its VAR increases between 0-1,72 m from 0,87 mm to 1,51 mm as the influence of degradation diminishes.

The age of the peatland also plays a role when considering carbon accumulation (Clymo et al., 1998). Dead parts of plants which become part of the catotelm still undergo anaerobic decomposition, mainly by anaerobic bacteria performing different reduction processes (Clymo et al., 1998; Succow and Joosten, 2001). This anaerobic decomposition takes place much slower than aerobic decomposition; however, it results in a net loss of carbon through the emission of CH_4 and leaching of carbon compounds (Alm et al., 1997; Clymo et al., 1998). Different hydrological periods which superseded each other at site VB (indicated by changing substrates) make it impossible to estimate the effect of anaerobic decomposition. Yet, the accumulation rates derived for the deeper horizons at site VB and hence the LORCA are somewhat underrated, in comparison with site ID.

As the permanence of water saturation and inundation determines the decomposition rate, the hydrological conditions of a peatland play a role in accumulation rates as well. On average, the VAR for the terrestrialisation part of site VB (which accumulated gyttja) is 1,03 mm/yr, whereas the mean of the peat accumulation under drier conditions lies at 0,64 mm/yr. Obviously, in strongly seasonal South Africa, terrestrialising peatlands with higher water levels and longer periods of inundation are the better accumulation systems.

Furthermore, the lower accumulation rates during drier conditions are probably connected to fire, which is another important limiting factor to peat accumulation (Tolonen and Turunnen, 1996). VB-3 has the highest frequency of charcoal. Its carbon accumulation rate (26 $gCm^{-2}yr^{-1}$) is correspondingly the lowest of the whole record. The highest values were ascertained for gyttja (ID-1 - ID-5: 102 $gCm^{-2}yr^{-1}$; and VB-2: 76 $gCm^{-2}yr^{-1}$), due to their fine texture and high bulk density; and wood peat with 91 g C m^{-2} yr^{-1} which is during its accumulation mostly spared by fire.

On a global scale, the LORCA values reflect above average peat productivity of tropical peatlands (Page et al., 2004). In temperate regions reported LORCA values are lower, for example between 9 and

35 $gCm^{-2}yr^{-1}$in Finland (Tolonen and Turunnen, 1996), and 9 and 41 $gCm^{-2}yr^{-1}$ in Canada (Loisel and Garneau, 2010). Reported values for tropical peatlands are higher. Averages for Indonesian peatlands range between 56 and 70 gCm^{-2} yr^{-1} for peat swamp forests in Kalimantan and Sumatra (Dommain et al., 2014; Page et al., 2004), with maximum values of up to 130 gCm^{-2} yr^{-1}. The derived LORCA values for the South African peatlands site VB =55 gCm^{-2} yr^{-1} and site ID = 89 gCm^{-2} yr^{-1} fit well with the Indonesian ones.

2.5.4 Fire

The almost gapless charcoal sequences at site ID and at site VB throughout the terrestrialisation stage (VB-2) and the subsequent open sedge-mire stage (VB-3), give evidence that fire is a common natural feature in this region. It must have occurred at least once every 10 years, considering that the peat cores were dissected in 1 cm slices. It can be assumed that fire occurred naturally, as the study sites are surrounded by a savannah-like vegetation of grass- and woodlands, which is prone to fire in dry seasons (Scott, 2002). Due to human activities such as the slash and burn practice, the frequency of fire increased in the last century (Grobler, 2009), which can be seen as well in site VB.

A low intensity fire which went over the peatland surface burning dry herbaceous vegetation was witnessed by the authors during fieldwork in March 2015. The water table at that point of time was measured as 3 cm below ground (Figure 2-5). Most of the soft parts of the dry vegetation like *Thelypteris interrupta* were burnt, but more stout species among the Cyperaceae, as well as *Phragmitis australis* survived.

Even though site ID provides evidence of regular fires since its initiation in 860 cal yr BP, charcoal is virtually absent in site VB, ever since the vegetation shift to peat swamp forest in 1206 cal yr BP. The macrofossil record indicates that fire is virtually not entering peat swamp forests, presumably because it doesn’t yield much dry combustible material. Also a development of an herbaceous layer is not common in wet peat swamp forest (Grobler, 2009).

2.5.5 Peatland development vs climate and sea-level changes

Climate, together with sea-level changes, plays an important role as a driver of peat formation on the Maputaland Coastal Plain. The groundwater level, which determines the peatlands' water supply, responds to the climate, which was since the early Holocene subject to some variations (Baker et al., 2014; Scott and Lee-Thorp, 2004). The beginning of the Holocene was characterised by arid conditions (Scott and Lee-Thorp, 2004) Approximately 7500 cal yr BP marks the transition to the temperature optimum of the Holocene, with a positive effect on the moisture in the summer rainfall region of South Africa (Scott and Lee-Thorp, 2004). This climatic shift was caused by an intensification of the Agulhas current that especially affected the KwaZulu-Natal province (Neumann et al., 2010). Further, the sea-level rose during the time between 10.000 cal yr BP and 7300 cal yr BP from -10m to 0m (Ramsay, 1995). Grundling (2004) argues that a rising sea-level in the first half of the Holocene led to a rising groundwater table on the Maputaland Coastal Plain. Dommain et al. (2014) investigated the same mechanism in Indonesia, where the post glacial sea-level rise led to the inundation of the Sunda Shelf. The elevated sea-level reduced the discharge of ground and surface water from the land masses and triggered peat formation in inland Borneo (Dommain et al., 2014). The sea-level rise still continued to the mid Holocene, albeit, at a slower rate (Ramsay, 1995). The deepest radiocarbon sample from site VB at 457 cm depth was dated to 6159-6166 cal yr BP. Considering the VAR of 0,99 mm/yr and the unsampled 10 cm of sand gyttja below, we suggest the first time of sedimentation of organic matter in ca. 6260 cal yr BP. It can be concluded that during this time the valley became inundated (macrofossils of *Nymphaea* sp.; *Utricularia* sp.; *Eleocharis dulcis; Schoenoplectus corymbosus* var. *brachyceras*). Hence, it appears likely that both climate change and sea-level rise triggered the peatland initiation in Matitimani valley. Figure 2-7 shows the relation of the geneses of the two study sites, with the sea-level curve (Ramsay, 1995) and the climate curve (Holmgren et al. 1999).

According to Ramsay (1995) the sea-level rose to a height of 3,5 m above the current sea-level in 5080 cal yr BP. Again, parallels to the tropical peatlands in Indonesia arise, where coastal peatlands at the east coast of Sumatra, in succession after mangroves, spread extensively with the stabilisation of sea-level at its Holocene highstand between 5400 and 5000 cal yr BP (Dommain et al., 2014). In South Africa, the sea-level fell afterwards to approximately the current height at about 4218 cal yr BP, with a very swift drop of almost 2 m until 4930 cal yr BP. This swift drop is thought to have had a considerable lowering effect on the groundwater level, and coincides in site VB with the shift from inundation dominated VB-2 to the drier period VB-3 (*Cyperus* sp., *Hydrocotyle bonariensis* and macrocharcoal) in 4946 cal yr BP.

Climate was supposedly also a driver for a ground water level drop. High δ^{18}O values and low δ^{13}C values in stalagmites of the Cold Air Cave in the Makapansgat Valley indicate that wet and moist conditions prevailed until about 5100 cal yr BP (Scott and Lee-Thorp, 2004). Pollen records from KwaZulu-Natal with high counts of *Podocarpus* confirm this assumption (Finch and Hill, 2008; Neumann et al., 2010). The time 5000 cal yr BP was characterised by aridification (Schott and Lee-Thorp, 2004). According to Neumann et al. (2010) this trend towards drier conditions prevailed on the Maputaland Coastal Plain, leading to a shift from *Podocarpus* to Poaceae pollen by ca. 3600 cal yr BP. Therefore, neither climate nor sea-level history suggest a further groundwater rise after the shift to VB-3. The lack of aquatic macrofossils in the record shows that no noteworthy inundation has taken place. However, since peat accumulation is always associated with at least steady near surface water conditions, the peatland water table must have been rising during that period. Despite the drier climatic conditions the peat remained saturated, possibly through a feedback mechanism whereby a slight increase in decomposition decreases downward infiltration and prevents rapid water loss from the mire. A moist period for the time between 5000 and 3500 BP, that Meadows (1988) deduced from increased peatland initiations in the central part of South Africa, cannot be confirmed by our results.

By 2480 cal yr BP, with the shift from VB-3 to VB-4, the drier period became superseded by a wetter period, which led to the inundation of the valley, as indicated by many seeds of the aquatic *Nymphaea* sp. Analysis of the above mentioned Makapansgat stalagmite confirm an extremely humid period from about 2500-2200 years BP (Holmgren et al., 1999). Another possible influence for the inundation could have been the closure of the estuary of the Kosi Bay lake system at its previous outlet at Bhanga Nek around 3000 BP (Wright et al., 1999).

The initiation of VB-5 displays a change from organic gyttja to peat, made of fine rootlets in a decomposed matrix. The macrofossil record displays an obvious lack of carpological remains, which may have been subject to decomposition, possibly as a result of a drop in the groundwater level when the Kosi Mouth formed in ca. 1500 BP as a new outlet of the lake system (Cooper et al., 2012). However, this hypothesis lacks hard proof at the moment.

The shift to peat swamp forest vegetation at ca. 1200 cal yr BP (at 1,72 m) is related to a short period of wet conditions. Oospores from the algae *Nitella* sp. between 1,79 and 1,70 m indicate inundation. Schoultz (2000) points out that in South Africa a substantial problem for the maturation of *Ficus trichopoda* dominated peat swamp forest is the regular exposure to fire, which destroys seedlings. The reduction of fire events during that interval, which is witnessed by the absence of macrocharcoal in the macrofossil record, ensured the necessary conditions for peat swamp forest to mature. The wet period could not be sourced in the literature, but it may be the same as that identified by Stager et al. (2013) - a few decades after 1350 cal yr BP (date recalibrated with SHCal13). Furthermore, it should be noted that due to the short duration of these climatic events, chronological uncertainties and wiggle matching complicate the picture of regional synchronous rapid climate change (Baillie, 1991; Blaauw, 2012) and the possible response of local plant communities in peatlands. High planktonic diatom percentages from Lake Sibaya indicate a short wet period (few decades), which probably had the highest precipitation of the past 2000 years (Stager et al., 2013). It seems likely that this inundation initiated the colonisation of site VB with peat swamp forest vegetation and therefore induced the shift from VB-5 to VB-6.

Shortly afterwards we estimate the peatland initiation at site ID. The deepest radiocarbon sample at 1,5 m depth was dated to 860 cal yr BP. Considering the VAR of 1,63 mm/yr and the unsampled 10 cm below, we suggest the earliest gyttja sedimentation at ca. 920 cal yr BP. This coincides with a wet period Holmgren et al. (1999) determined between 1000 and 900 BP (Figure 2-7). However, it is unlikely that climate alone initiated the peatland initiation at site ID, since it did not take place in earlier wet periods. Looking at the greater picture, the Matitimani-valley lies about 11 m lower than site ID and drains the groundwater of the surrounding area towards Lake Nhlange. It must be concluded that the peat development in the drainage line has a congestive effect, which reduce the discharge and leads to the elevation of the groundwater level in the catchment above (Figure 2-8). The same effect was witnessed by Grundling et al. (2013) for the Mfabeni mire.

Since its initiation site ID developed gradually. The first 0,4 m of peatland substrate are built up by sand gyttja which accumulated during inundation, with the aquatic *Nymphaea* sp. as the dominant plant in this period. Charcoal pieces and seeds of more terrestrial species like *Pycreus polystachyos* point out that inundation retreated regularly, as a consequence of the strong seasonality. Between ID-1 and ID-2 a shift to drier conditions took place, most likely coinciding with the start of the Little Ice Age between 650 and 150 cal yr BP (Holmgren et al., 1999). According to Holmgren et al. (1999) in South Africa this time was associated with "*aridification and an increase in frequency of major flood events*". This would explain the mixed aquatic-semiaquatic macrofossil record in ID-2, ID-3 and ID-4. The gradual shift in the macrofossil record towards drier vegetation (decrease of *Nymphaea* sp., increase of *Cyperus* sp.) was interrupted by the much wetter period (ID-5; 0,27-0,14 m). A dendrochronological investigation of a *Podacarpus* tree from KwaZulu-Natal indicates outstandingly wet conditions between 160 and 110 cal yr BP (Hall, 1976). The dating sample from 0,22-0,21 m (at 130 cal yr BP) coincides with this wet period, supporting the idea that climate was the dominant influence at that time. The imprint of this period, however, is not visible in the record for site VB, because it doesn't have the same preconditions for inundations as the closed interdune depression. The shift to drier conditions from ID-5 to ID-6 entailed the establishment of the current Cyperaceae-dominated, peat accumulating, vegetation type; even though aquatic seeds of *Nymphaea* sp. and *Utricularia* sp. prove regular inundations.

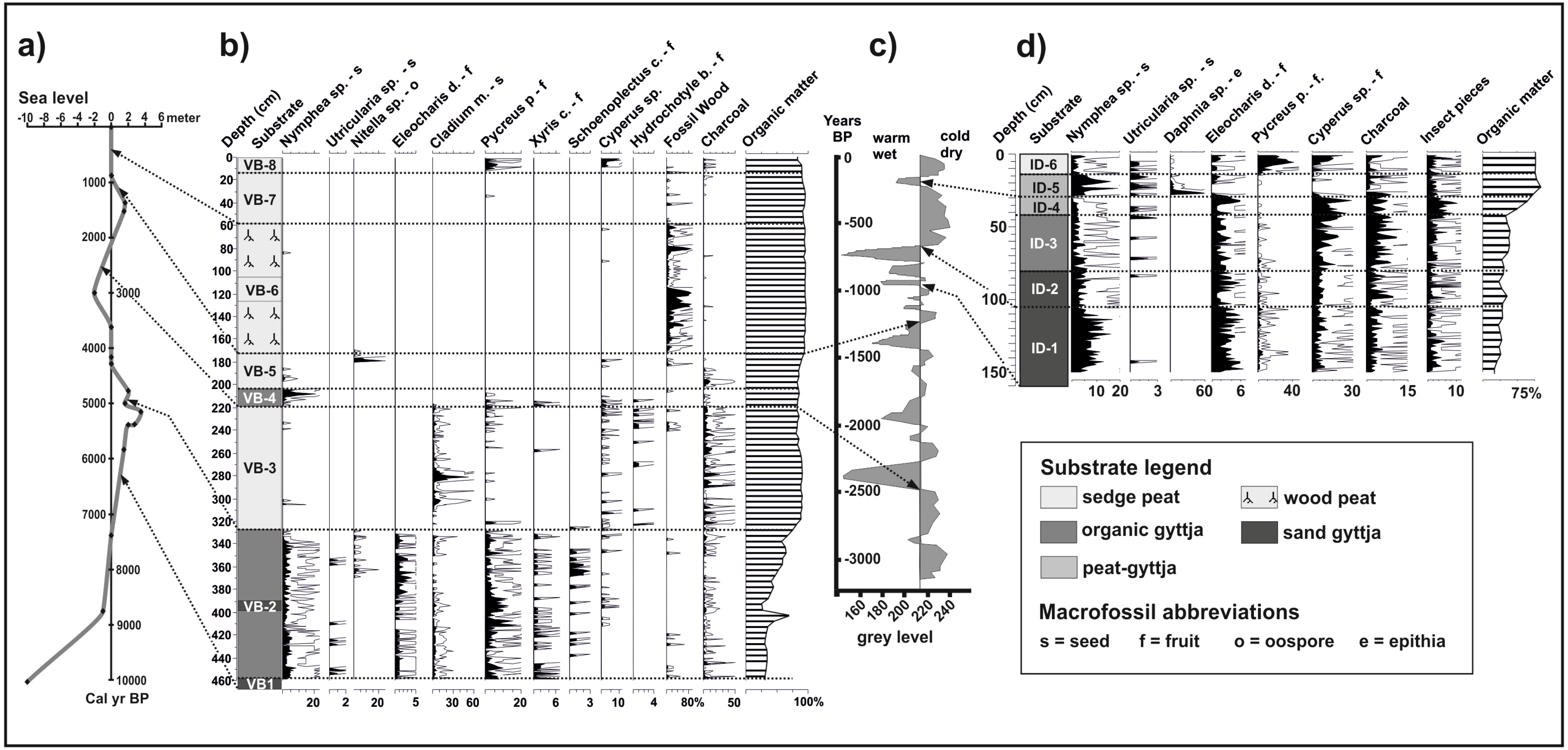

Figure 2-7: Peatland geneses, climate and sea-level change during late-Holocene: **(a)** sea-level curve, adapted from Ramsay (1995); **(b)** macrofossil record site VB, selected species; **(c)** climate curve derived from grey level analysis of a stalagmite from Makapansgat cave, adapted from Holmgren et al. (1999); **(d)** macrofossil record site ID, selected species.

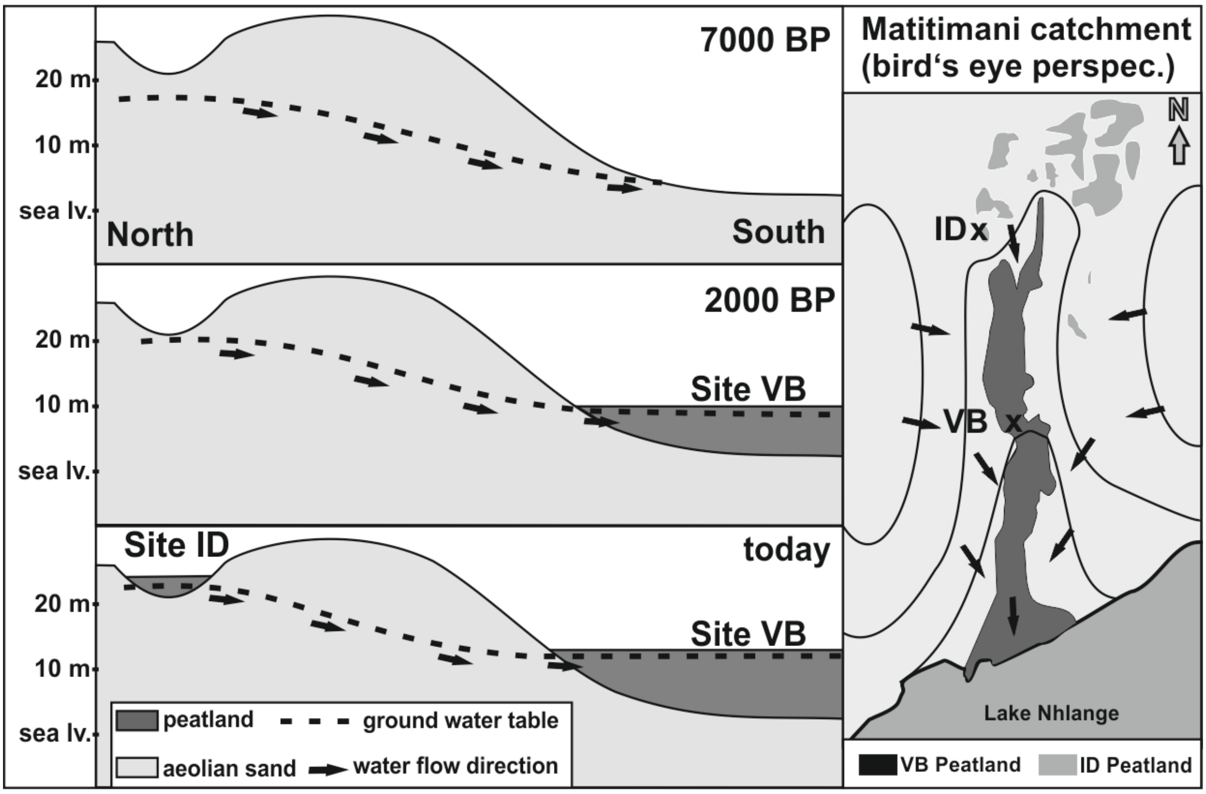

Figure 2-8: Schematic rise of water table in Matitimani valley and the above-lying site ID throughout the last 7000 years (left); schematic groundwater discharge towards Lake Nhlange (right).

2.6 Conclusions

Groundwater determines the accumulation of organic substrates in Maputaland. Throughout the Holocene, climate and sea-level directly affected the height of the groundwater.

The initiation of the peatland at site VB coincides with a high sea-level stand and a moist climatic period during the early to mid-Holocene. The late initiation of the peatland at Site ID is a product of the establishment of a profound peat layer in the Matitimani-valley which led to a rise in the groundwater level in the catchment. A further degradation of the valley-bottom peatland in Matitimani would also result in the degradation of the interdune depression wetlands, as with the subsidence of peat in Matitimani a reverse of the groundwater rise in the surrounding catchment can be expected. Further, this highlights the importance of the wise and sustainable management of peatlands, which are situated in lower catchments.

Ficus trichopoda, *Syzygium cordatum* and *Voacanga thouarsii* are the dominant wood peat-forming species. Carpological findings suggest that *Nymphaea* sp. and *Eleocharis dulcis* are strongly related to the accumulation of detritus, forming organic gyttja. Various *Cyperus* species and *Pycreus polystachyos* have a dominant role in the formation of radicell peat.

Fires occur frequently on nonforested peatlands. Peatlands in South Africa are extremely vulnerable to fire in above-average dry years, e.g. shown by the fire history of the Vazi-peatland (Grundling and Blackmore, 1998). Peat swamp forest serves as a natural protection. Cutting trees means exposing the peatland to fire risk.

The natural occurrence of fire is a limitation is a factor slowing down peat accumulation. The highest carbon accumulation rates were therefore determined for wood peat from peat swamp forest and gyttja.

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2.9 Supplementary Material

Supplementary material 1: Morphological description of the encountered substrates. Descriptions derived from the German Pedological Mapping Directive KA5 (Ad-hoc-AG Boden 2005)

Substrate designation	**Characteristic**
Wood peat	Peat with more than 15 % dead woody plant material. Soft, fibrous and with low von Post decomposition grades; colours: yellow, red and brown. Typically with fine dark radicells.
Amorphous peat	Peat without identifiable plant remains and with high to maximal degree of decomposition; colour: brown to black.
Radicell peat	Peat composed of fine and hollow radicells / radicell fragments mostly from Cyperaceae in different degrees of decomposition; colour: yellow to brown.
Saw-sedge peat	Peat mainly formed from the stem bases of *Cladium mariscus* subsp. *jamaicense;* mainly consisting of fibrous material; possibly accompanied by organic gyttja and radicells; colour: dark red. Easily confusable with wood peat.
Reed peat	Peat formed mainly by the flattened (and fine layered) rhizomes of *Phragmitis australis,* possibly mixed with organic gyttja and radicells; colour: yellow-orange.
Coarse sedge peat	Peat mainly formed out of (flattened) stem bases of Cyperaceae; colour: yellow to brown.
Peat-Gyttja	Mixture of peat (radicells) and organic gyttja in apparently same quantities; colour: different brown shades.
Organic gyttja	Detritus or organic gyttja, with more than 30 % organic matter; most frequently occurring limnic sediment; colour: gray to black with slight olive tint
Sand gyttja	Organo-mineral limnic sediment, with organic matter content from 5 to 30 %; mainly composed of sand with noticeable content of organic matter; colour: grey to black

Supplementary material 2: Recalibrated dates for sea-level heights from Ramsay (1995).

According to Ramsay (1995)		**Calibrated with SHcal13**			**Sea-level height***
C14-Date	**Error +-**	**From**	**To**	**Mean**	[m]
910	120	1049	564	**807**	0
920	140	1062	560	**811**	0
1450	50	1410	1186	**1298**	1,6
1610	70	1594	1309	**1452**	1,5
3000				**3000****	-2
3360	60	3696	3400	**3548**	0
3780	60	4296	3896	**4096**	0
3880	60	4423	4012	**4218**	0
4240	60	4861	4532	**4697**	2
4350	60	5215	4644	**4930**	1,61
4480	70	5291	4869	**5080**	3,5
4650	60	5576	5050	**5313**	2,75
4660	50	5577	5060	**5319**	2
5080	70	5921	5613	**5767**	1,5
6460	80	7475	7172	**7324**	0
7840	90	8977	8409	**8693**	-1
8950	80	10228	9711	**9970**	-10

* referring to the current sea-level

** date in original source was estimated by Ramsay (1995)

3 Peatland substrates in northern KwaZulu-Natal - A study of the forming environments, properties and an approach towards classification

Marvin Gabriel[1], Camelia Toader[1], Franziska Faul[2], Niko Roßkopf[1], Piet-Louis Grundling[3], Cornelius van Huyssteen[4], Jutta Zeitz[1]

[1] Faculty of Life Science, Humboldt-Universität zu Berlin, Berlin, Germany

[2] Faculty of Earth and Environmental Sciences, University of Potsdam, Potsdam, Germany

[3] Centre for Environmental management, University of the Free State, Bloemfontein, South Africa

[4] Department of Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein, South
Africa

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Abstract

Peatlands in South Africa are rare, they fulfil important ecological functions but are threatened by degradation. Because of this they have gained increasing attention from scientists during the last two decades. However, knowledge about the peatland substrates and the means to classify them is limited. This study was conducted in peatlands of the Maputaland Coastal Plain. Its approach uses the German Soil Mapping directive “KA5”, which acknowledges the accumulation process of substrates and botanical peat types. The aims were to investigate which substrates occur, if they have affinities to certain hydrogeomorphic wetland types (HGMTs) and to determine the physical and chemical properties. Seven peatlands in five different HGMTs were investigated along 19 transects with 141 soil profiles and 674 horizons. In total 15 different peatland substrates were encountered and characterised, amongst them raphia peat, ficus peat and peat-gyttja, which have not been described before. Mean values were determined for: organic matter content, bulk density, degree of decomposition, porosity, pH, and C/N ratio. A substrate reference scheme was also developed and classifies the encountered substrates with respect to their occurrence in HGMTs.

Keywords: hydrogeomorphic wetland types, peat properties, mire substrates, South Africa, Maputaland

3.1 Introduction

South Africa is a country with vast dry tracts of land, but also has regions in which peatlands[2] occur (Grundling and Grobler 2005). Due to the generally arid climate, peatlands present azonal features and are usually found in places where groundwater influx exceeds the loss through evapotranspiration (Mucina and Rutherford 2006; Grundling 2014). Hence, the landscape setting, the source of water and the constancy of water supply throughout the seasons play an important role in the formation of peat. Distinct combinations of these factors generate specialist vegetation-communities adapted to the hydro-ecologic conditions of the habitat (Joosten and Clarke 2002). Plant residues of these different vegetation-communities on the one hand, and different intensities of microbial activity on the other, eventually lead to the formation of distinct peatland soil substrates (Succow and Joosten 2001).

In some South African regions peatlands are very important as sources of water; they retain the water from the precipitation in the geographical area either with their high water storage capacity or as flow regulation, which impedes a rapid discharge. Their fertility makes them favourable for crop cultivation (Grundling and Grobler 2005, Grundling et al. 2016). In many cases cultivation practices

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[2] Next to the term **peatland***,* which generally refers to areas were peat is found at the surface, the term **mire** is also used in this study, referring to peatlands with a currently forming peat layer (Joosten and Clarke 2002). Even though, mire is excluding drained and degraded peat areas, it will later be applied, associated with the concepts of ecological mires types (Succow and Joosten 2001), for all sites indistinctively.

include drainage of saturated organic soils, exposing the top 30 to 50 cm to aerobic conditions with consequent mineralisation (Grobler 2009; Arndt 2013; Faul et al. 2016). The establishments of *Eucalyptus* plantations, which excessively deplete the local groundwater tables, results in a drying of the peatlands (Pretorius et al. 2014; von Roeder 2015, Grundling et al. 2016). Due to these activities South African peatlands are endangered while various soil-related questions regarding their ecological functions remain unanswered. For the investigation of soil-related issues, a classification of soil substrates and soil types is an important tool. It allows the researcher to estimate soil qualities and functions by comparison with reference soil types or reference soil substrates.

Despite their local importance, the peatlands of South Africa were relatively under researched until the 1990s, due to a relatively small surface cover of approximately 298 km² (Marneweck et al. 2001) representing less than 0.03% of South Africa's land area. Landmark studies on South African peatlands are rather young (Smuts 1997; Grundling et al. 1998; Grundling 2001; Grundling and Grobler 2005). Due to the dearth of research the South African soil classification system "The Blue Book" does not pay particular attention to peatlands (Soil Classification Working Group 1991). It is a detailed guideline to describe mineral soils but lacks options to adequately describe the ample types of organic soils in South African peatlands. No specification of peatland substrates is drawn. For example, gyttja, a substrate forming out of particles which are sedimented at the bottom of water bodies, is not distinguished; even though it is frequently encountered in peatlands, where it gives evidence of former limnic stages of peatland formation. With the current classification system, all peat soils are classified as Champagne soil forms and are then further categorised into four soil families, based on the fibrous or humified state of the peat and different underlying material (Soil Classification Working Group 1991). Smuts (1996, 1997), investigated the South African peatlands as a possible fuel source, differentiating between the four types hardwood swamp forest, reed/sedge fen, mangrove forest and *Raphia* palms, according to the dominant peat-forming vegetation. Smuts further designed a classification approach for fen peatlands according to their topography. Another approach was developed by Ollis et al. (2013): "The Classification System for Wetlands and other aquatic ecosystems in South Africa". It distinguishes hydrogeomorphic wetland types (HGMTs), according to the geomorphic setting, the water source and the hydrodynamics; based on a system originally developed by Brinson (1993). They further adapted the definition of peat to the international understanding of "material with an organic matter content of at least 30%" (Joosten and Clarke 2002; Ollis et al. 2013). Although HGMTs are a useful concept for the classification of peatland types, which can also be utilised by remote sensing techniques (Grundling 2014), the possibilities for the characterisation of peatland substrates are rather poor.

To create a more solid foundation for research and decision making, we propose a detailed description of South African peatland substrates. For this purpose we chose to follow the German Soil Mapping Directive "KA5" (Ad-hoc-AG Boden 2005). Germany, a country with a long history of peat mining and agricultural use of peatlands, developed a detailed classification method for the evaluation of peat characteristics. Firstly, it categorises different peatland substrates into peat and gyttja, according to the accumulation process. Secondly, it divides them into subgroups. According to the species or vegetation community forming the residues, different botanical peat types are distinguished. This botanical differentiation of peat types also gives the German system an advantage over the internationally used Guidelines for Soil Description (FAO 2006) and US Soil Taxonomy (USDA 2014), which likewise lacks this distinction. Peat types which do not occur in temperate Europe and which are not included in the German Soil Mapping Directive “KA5” were similarly described according to their main botanical components.

Within South Africa the greatest variety of peatlands in different HGMTs can be found on the Maputaland Coastal Plain (Grundling 2014). For this reason the region was chosen as a study area for the investigation of peatland substrates. The first aim of this study was to characterise the existing peatland substrates, including their physical and chemical properties. The second aim was to characterise the different hydrogeomorphic wetland types and to determine their typical substrates. The third aim was to propose a substrate reference scheme, with respect to the hydrogeomorphic wetland types.

3.2 Study area

The study area (Figure 3-1) lies within a radius of 20 km around the town Manguzi, in northern KwaZulu-Natal. The climate is subtropical-tropical with a mean monthly maximum of 26°C in February and a mean monthly minimum in June of 17°C (Lubbe 1997; Maud 1980). The annual precipitation of 950 mm is roughly double that of the South African average. The potential evapotranspiration reaches 2200 mm per annum (South African Risk and Vulnerability Atlas 2009). Two thirds of the rainfall occurs from October to March, with a great variability between the rainy seasons (Grundling 2014). The study area is located on the Maputaland Coastal Plain, stretching out from Maputo in Mozambique 300 km southward down to Mtunzini, covering the northern most section of the South African east coast (Grundling 2014).

The vegetation zone is known as the Maputaland Coastal Belt and exhibits edaphic grasslands and coastal forests as main zonal vegetation types (Mucina and Rutherford 2006). Due to many microhabitats and an overlap between tropical and subtropical vegetation the region is rich in endemism and biodiversity (Smith and Leader-Williams 2006). Thus, one also finds many azonal vegetation types like swamp forests, mangrove forest, subtropical dune thickets and freshwater wetlands (Mucina and Rutherford 2006).

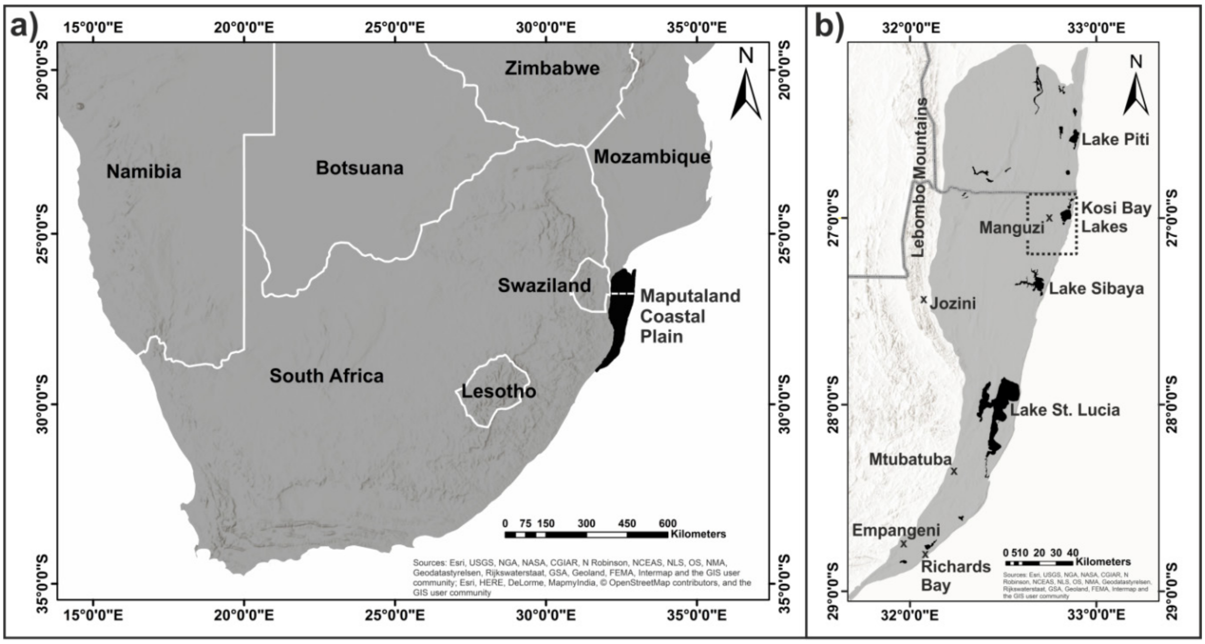


Figure 3-1: **(a)** Position of the Maputaland Coastal Plain (black) in Southern Africa; **(b)** Situation of the study area (dashed box) on the Maputaland Coastal Plain, water bodies in black (Maps compiled with Esri maps "World hilllshade" and "World Countries").

The landscape of the Maputaland Coastal Plain is dominated by undulating dune topography, consisting of a layer of unconsolidated aeolian sand, namely the KwaMbonambi formation (Botha and Porat 2007). This sand was successively mobilised and redistributed during the last glacial cycle until around 9000 years BP, when it was stabilised by emerging vegetation (Maud 1980; Botha and Porat 2007). Underneath the KwaMbonambi Formation, which varies in depth between 10-20 m, lies a stratum of sandy silts with moderate clay contents, namely the Kosi Bay Formation (Botha and Porat 2007; Grundling 2014). It acts as a partial aquiclude due to its finer texture. As a consequence, one finds a shallow aquifer within the KwaMbonambi-cover sands. In some places, this shallow aquifer is in contact with the surface, causing soil saturation or even discharge as surface water (Botha and Porat 2007). In these places peatlands can develop as anaerobic conditions impede the microbial activity and decelerate the decomposition of organic material. This can occur in different topographic settings. A previous investigation by Grundling (2014) applied the concept of HGMTs to the north-eastern section of the South African part of the Maputaland Coastal Plain and identified five different types (Table 3-1).

Table 3-1: HGMTs of the north eastern section of the South African part of the Maputaland Coastal Plain (according to Grundling 2014) and there coverage. The missing 9% of the wetland area are lake bodies.

Hydrogeomorphic wetland type	Characteristics	Wetland area
Channelled Valley-Bottom [CVB]	Situated adjacent or close to a distinct active channel of a river, located on a valley floor, with **no** river-derived depositional features characteristic of a floodplain. Water input via (surface and subsurface) runoff from one or both of the adjacent valley side-slopes.	11%
Unchannelled Valley-Bottom [UVB]	Located on a valley floor, without clearly discernible channel banks characterised by permanent or periodic, diffuse, unidirectional through-flow of water (often dominated by subsurface flow).	36%
(Interdune) Depression [ID]	An area characterised by closed (or near-closed) elevation contours within which water typically accumulates. It includes areas not fed by water from a river channel, typically located on a lowland (plain) or a upland (plain), not necessarily completely flat, but can slope up to 0.3%, although more typically a lower order of magnitude. Water movements include vertical (flip-flop) and horizontal (through-flow).	35%
Seep [SP]	Not located on a valley floor and without clearly discernible channel banks. Characterised by permanent or periodic, diffuse, unidirectional through-flow of water (often dominated by subsurface flow).	8%
Floodplain [FP]	Situated adjacent or close to distinct active channel of a river, located on a valley floor, with river-derived depositional features and water input from periodic (intermittent to seasonal) overtopping of the channel banks.	1%

3.3 Methods

As a first step, Google Earth was used to investigate satellite-images of different years and seasons. Sites which maintained green cover throughout the dry seasons were marked as possible study sites. Based on their shape (e.g. enclosed, linear, linear with connection to a waterbody, etc.) 15 sites in different HGMTs were identified. The sites were then visited with a Russian peat corer, (manufacturer: Eijkelkamp), extracting half-cylindrical cores of 50 cm length and about 560 ml volume. In that way, the central parts of the sites were tested for the existence of a peat layer.

Six peat containing sites were designated as study sites, to cover the four main HGMTs at least once, as well as a gradient of degraded, succession and pristine sites (Figure 3-2, Table 3-2). A seventh site (FP) was elected to study in particular the very rare substrate raphia peat, which was not found at the first six sites and whose presence was known at the site FP by a former study (Smuts 1997).

The main tool for the field sampling was the Russian peat corer. The profile description was based on the German Soil Mapping Directive “KA5” (Ad-Hoc AG Boden 2005). The actual investigation was conducted along transects, creating soil profiles in regular intervals along a linear direction through the peatland. In this way the stratigraphies of the peatlands’ cross sections were explored. Altogether 19 transects were investigated containing a total number of 141 profiles containing peatland substrates (Table 3-2).

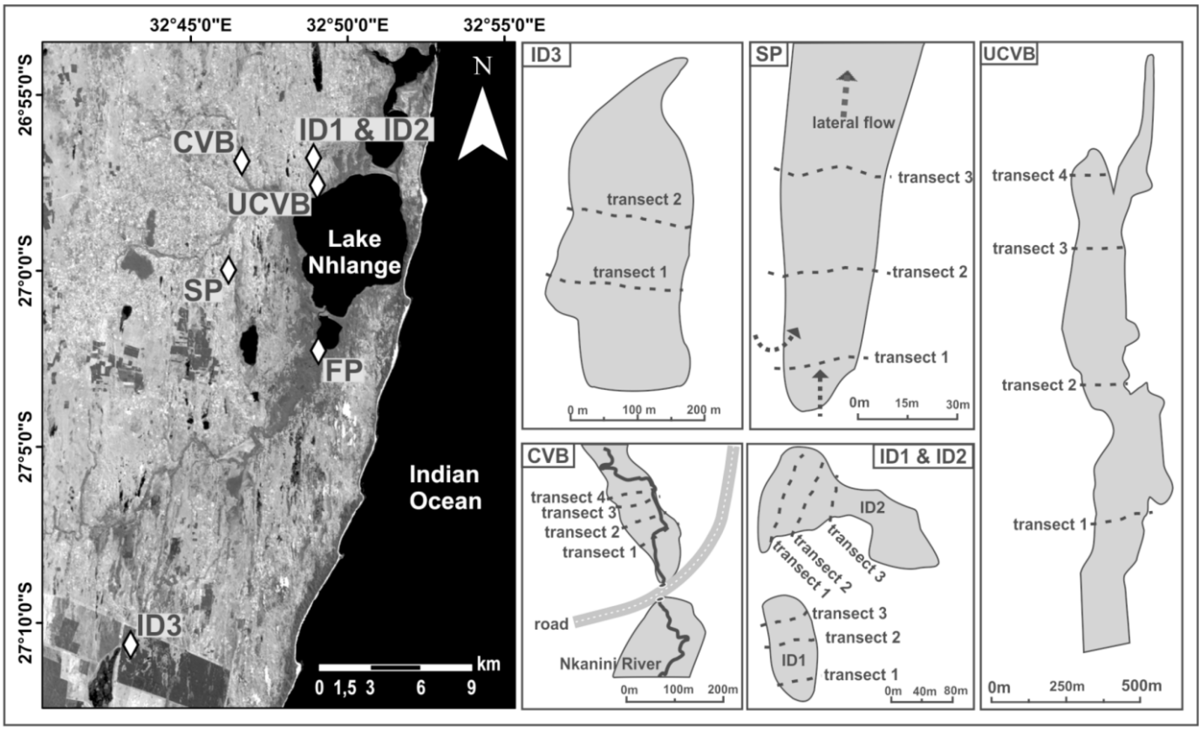


Figure 3-2: left: overview of the study sites (abbreviations according to **Table 3-2**); right: shape of study sites (peatland surface in grey) and position of transects. Satellite image was acquired by LANDSAT 11th August 2001.

One profile was subsequently chosen for each transect as a site-characteristic profile, with respect to the maximum peat thickness and typical horizon combination. Each horizon of the site-characteristic profile was sampled and analysed for pH, electric conductivity, total nitrogen and total carbon, according to the methods given in Table 3-3. Further, the degree of peat decomposition was determined with the squeezing method of von Post (1922). In this simple test, one takes a chicken-egg sized sample of wet peat in the hand and squeezes. According to the colour of the water or the quantity of material remaining in the hand, the decomposition is determined on a scale of ten stages from undecomposed (H1) over moderately decomposed (H5) to completely decomposed (H10) (also see Faul et al. 2016).

The surface reachable horizons (to approximately 120 cm depth) were sampled with volumetric sample rings (82 cm³) for bulk density and total pore volume. Bulk densities for deeper samples were determined by drying volumetric sections (130 cm³) from the peat cores. In addition, substrates which were encountered in the stratigraphies, but not in the site-characteristic profiles were sampled separately for laboratory examination. For only four of these extra samples total carbon and total nitrogen were determined (1x ficus peat, 1x saw-sedge peat and 2x coarse sedge peat), whereas organic matter was mostly analysed by loss on ignition. A conversion factor of 1.88 was used to convert (organic) carbon, determined with the element analyser, into organic matter, as proposed by Farmer et al. (2014) for tropical peat.

Table 3-2: Overview of study sites and transect. Pri.=pristine; Suc.=succession after cultivation; Deg.=degraded.

Site name	Hydrogeomorphic wetland type	Local name/ coordinates	Size (ha)	Condition; use	Tran-sects	Profiles
CVB	Channelled valley-bottom	Nkanini River 26°56'52.89"S 32°46'37.99"E	2[a]	Suc.; -	4	39
ID1	Interdune depression	KwaMazambane 26°56'52.50"S 32°48'54.57"E	0.2	Pri.; cultivation at fringe	3	17
ID2	Interdune depression	eMdoni 26°56'46.81"S 32°48'54.14"E	1.4	Pri.; cultivation. at fringe	3	22
ID3	Interdune depression	Vazi North 27°10'39.58"S 32°43'3.83"E	15	Deg.; cattle herding	2	20
UVB	Unchannelled valley-bottom	Matitimani 26°57'21.50"S 32°48'59.83"E	38.6	Transects a-c: Suc. Transect d: Pri.	4	31
FP	Floodplain	Siyadla River 27° 2'16.83"S 32°49'3.19"E	2-3[b]	Pri; -	0	1
SP	Seep	Nkatwini 26°59'58.23"S 32°46'12.57"E	0.2	Deg.; cultivation	3	11

[a] The given size in the case of CVB refers to the investigated portion of the much larger peatland.

[b] The given size refers to two delimited neighbouring peatland areas on the much larger flood plain, which possibly hosts other areas withpeat substrates

Table 3-3: Summary of field and laboratory methods.

Soil Property	Method	Reference
	Field measurements	
Degree of decomposition	Squeezing test (von Post)	Von Post (1922)
pH-value	Field electrode (Eutech CyberScan PC 650)	Eutech Instruments (2011)
Electric conductivity	Field electrode (Eutech CyberScan PC 650)	Eutech Instruments (2011)
	Laboratory analyses	
Bulk density	Drying of volumetric samples (48 hours, 105°C)	DIN EN 15934: 2012-11
Total pore space	Derived from weight loss of saturated bulk density samples (48 hours, 105°C)	Derived from: DIN EN 15934: 2012-11
Total nitrogen	TruSpec CHN-Determinator (LECO Corporation)	LECO (2016)
Total carbon	TruSpec CHN-Determinator (LECO Corporation)	LECO (2016); DIN ISO 10694: 1994
Organic matter	Loss-on-Ignition 550°C	Schulte and Hopkins (1996)

A classification of the peatland substrates was derived on the basis of hydrogeomorphic wetland types (Ollis et al. 2013) and the botanical peat types (Ad-Hoc AG Boden 2005). Further, the application of another classification method by Succow and Joosten (2001) was tested, which distinguishes ecological mire types according to their trophic status (C/N) and base saturation (pH-value) (see Table 3-4).

Table 3-4: Ecological mire type according to Succow and Joosten (2001).

Ecological parameter	**oligotrophic - acid**	**mesotrophic - acid**	**mesotrophic - subneutral**	**mesotrophic - alkaline**	**eutrophic**
$pH_{(KCl)}$	≤4.8	≤4.8	4.8-6.4	6.5-8.5	3.2-7.5
C_{org}/N	>33	20-33	20-33	20-33	<20

3.4 Results

3.4.1 Transects and substrates

Altogether 15 peatland substrates were recorded and characterised (Table 3-5). Seven of them had already been described by the German Soil Mapping Directive “KA5” (Ad-hoc-AG Boden 2005). Eight substrates were not covered by this system: Raphia peat, ficus peat, coarse sedge peat, wood-radicell peat, peat-gyttja, colluvial organic substrate high in organic matter (OM), colluvial organic substrate low in OM and alluvial loam rich in OM. The description of their morphology and peat-forming macrofossils was conducted through this study.

A depiction of one selected transect from each site showing the stratigraphy is given in Supplementary Material 1-8. Because site UVB exhibits a greater diversity with areas in different stages of human impact, four transects were analysed to account for these differences. Because of a generally very shallow peat layer, site FP was not described along a transect, a single soil profile from the location with the greatest vertical peat extent (55 cm) was investigated (Supplementary Material 9).

Table 3-5: Description of found substrates, (partly adapted) from the German Soil Mapping Directive "KA5" (Ad-hoc-AG Boden 2005).

Substrate	Morphological description
Radicell peat (in other literature sometimes sedge peat)	Peat composed of fine and hollow rootlets / root fragments (< 1mm) in different degrees of decomposition; colour: yellow to brown. Mostly accumulated from Cyperaceae.
Coarse sedge peat	Peat accumulated from the stem bases of Cyperaceae; mostly flattened cylindrical segments of 0.5- 2 cm in diameter and 1-5 cm in length, accompanied by smaller radicells; mostly in low to medium degrees of decomposition; colour: yellow to brown.
Saw-sedge peat	Peat formed from the stem bases of *Cladium mariscus* subsp. *jamaicense;* mainly consisting of fibrous material; colour: dark red. Easily confusable with wood peat.
Reed peat	Peat mainly consisting of flattened rhizomes of *Phragmitis australis* 1-3 cm broad; typically characterised by low to medium degrees of decomposition; colour: yellow to brown.
Wood peat	Peat mainly consisting of dead woody plant material. Soft, fibrous and usually with low von Post decomposition degrees; colours: yellow, red and brown. Typically with fine dark rootlets.
Wood-Radicell peat	Mixture of radicell peat and wood peat, possibly with stem bases of Cyperaceae. Colour: yellow-brown; with residues of *Ficus trichopoda* or *Syzygium cordatum* reddish.
Ficus peat	Peat mainly formed from dead woody plant material, dominant wood type *Ficus trichopoda*, characteristically with prominent fibres and dark red colour.
Raphia peat	Peat from roots (pneumathodes) of the palm *Raphia australis;* main component is a brownish amorphous matrix with radicells, which are hollow, slightly broader than sedge radicells and of a white-yellow colour.
Amorphous peat	Peat without identifiable plant remains but with a high to maximum degree of decomposition; colour: brown to black. Frequently occurring as dry topsoil of drained peatlands. Develops different structures according to the intensity of mineralisation.
Peat-Gyttja	Mixture of peat (radicell) and organic gyttja in apparently equal quantities; colour: different shades of brown.
Organic gyttja	Detritus or organic gyttja, with more than 30% organic matter; most frequently occurring as limnic sediment; colour: grey to black with slight olive tint.
Sand gyttja	Organo-mineral limnic sediment, with organic matter content from 5 to 30%; mainly composed of sand with noticeable content of organic matter; colour: grey to black.
Colluvial organic substrate high in organic matter	Substrate of sand and organic matter (**>30%**). Develops when sand is deposited in wet organic substrate accumulating footslopes.
Colluvial organic substrate low in organic matter	Substrate of sand and organic matter (**<30%**). Develops when sand is deposited in wet organic substrate accumulating footslopes.
Alluvial loam rich in organic matter	Fluviatile sediment, deposited during floods. Its texture varies and can comprise clay and silt in the mineral fraction as well, next to sand. Content of organic matter >5%.

3.4.2 Substrate properties

In total 674 horizons were recorded. Table 3-6 shows the frequency of occurrences of each substrate and the mean degree of peat decomposition according to von Post (1922).

Table 3-6: Substrates: Frequency of occurrence; DD=mean degree of peat decomposition; SD=standard deviation; OM=mean organic matter content in %; [N]=sample size; BD=mean bulk density; pf0=mean total pore volume; N=mean nitrogen content in %; C/N=mean nitrogen to carbon ratio; pH=mean pH-value measured in H_2O; "-"=not determined; n.a.=not applicable.

Substrate	[N]	DD	OM	BD	pf0	N	C/N	pH
Radicell peat	147	6.1 (1.7) [147]	75.0 (13.7) [18]	0.12 (0.05) [16]	94.3 (2.3) [11]	1.7 (0.3) [15]	23.5 (4.5) [15]	4.5 (0.4) [12]
Coarse sedge peat	8	5.1 (1.5) [8]	93.0 (2.3) [4]	0.10 (0.01) [20]	93.4 (2.0) [12]	1.6 (0.3) [2]	19.1 (4.5) [2]	4.8 (0.1) [2]
Saw-sedge peat	3	5.7 (2.1) [3]	92.7 (1.1) [4]	0.10 (0.01) [11]	92.0 (3.1) [6]	1.0 (-) [1]	41.1 (-) [1]	4.9 (-) [1]
Wood peat	58	6.1 (1.7) [58]	82.2 (8.2) [13]	0.12 (0.02) [11]	95.7 (0.5) [3]	1.4 (0.3) [8]	31.5 (6.3) [8]	5.1 (0.3) [8]
Wood-Radicell peat	38	6.2 (2.2) [38]	81.2 (11.2) [12]	0.09 (0.02) [15]	96.3 (1.8) [7]	1.8 (0.3) [8]	24.1 (5.8) [8]	4.5 (0.4) [7]
Ficus peat	2	4 (1.4) [2]	93.6 (5.0) [3]	0.10 (0.01) [3]	94.2 (0.4) [2]	0.7 (-) [1]	68.0 (-) [1]	4.7 (-) [1]
Raphia peat	4	5.8 (2.5) [4]	61.9 (6.0) [4]	0.18 (0.05) [4]	95.2 (2.1) [3]	1.5 (0.4) [4]	22.1 (3.4) [4]	6.1 (0.3) [4]
Amorphous peat	84	10 (0) [84]	62.8 (15.2) [25]	0.26 (0.07) [29]	90.6 (3.5) [11]	1.9 (0.8) [14]	19.4 (7.6) [14]	4.2 (0.3) [12]
Peat-Gyttja	69	n.a.	66.9 (16.6) [8]	0.15 (0.04) [11]	93.9 (2.9) [7]	1.5 (0.3) [5]	26.6 (3.7) [5]	4.4 (0.3) [5]
Organic gyttja	82	n.a.	56.1 (17.9) [15]	0.19 (0.06) [15]	92.1 (3.4) [2]	1.1 (0.3) [13]	27.7 (5.8) [13]	4.9 (0.4) [11]
Sand gyttja	78	n.a.	14.3 (6.2) [15]	0.63 (0.35) [15]	68.7 (25.7) [2]	0.3 (0.1) [11]	27.7 (4.7) [11]	4.6 (0.2) [11]
Colluvial >OM	19	n.a.	47.4 (0.3) [2]	0.35 (-) [1]	-	1.3 (0.3) [2]	20.0 (4.4) [2]	5.0 (0.1) [2]
Colluvial <OM	57	n.a.	8.7 (7.0) [11]	1.17 (0.34) [9]	46.7 (-) [1]	0.2 (0.2) [10]	24.1 (11.5) [10]	5.0 (0.6) [10]
Alluvial loam	19	n.a.	12.5 (5.3) [5]	0.99 (0.13) [4]	-	0.3 (0.2) [5]	21.4 (3.0) [5]	4.3 (0.6) [5]

Mean properties of the 15 encountered substrates are also given in Table 3-6. Organic matter, with concentrations over 90%, is highest in coarse sedge peat, saw-sedge peat and ficus peat. The most common substrate, radicell peat, with a mean organic matter concentration of 75% is furthermore characterised by a wide spread between 47 – 91% and consequently a greater standard deviation of 13.7%. Lower organic matter concentrations are observed in non-peat substrates, even though peat-gyttjas and organic gyttjas reach organic matter concentrations over 80%.

The bulk densities for peat substrates range between 0.09 and 0.12 g/cm³. Only raphia peat (0.18 g/cm³) and amorphous peat (0.26 g/cm³) have higher bulk density. The highest mean bulk density value (1.17 g/cm³) occurs in a colluvial organic substrate low in OM.

The C/N ratios indicate overall mesotrophic condition. Ficus peat and saw-sedge peat display high values and are therefore recognised as oligotrophic (nutrient poor) substrates. Merely amorphous peat with a C/N ratio of19 is recognised as eutrophic (nutrient rich).

Mean pH values determined in H_20 are between 4.2 and 5.1; except for raphia peat with a mean of 6.1. The lowest pH was measured in amorphous peat. According to van Lierop (1981) pH values of peat substrates can differ depending on the pH-determination. The more referenced KCl pH-determination, where H^+-ions from the soil surface are exchanged and enter the solution, usually yields values of about 0.4-0.7 units lower than in H_2O(van Lierop 1981).

3.4.3 HGMT substrate occurrences and properties

The frequency of substrate occurrences sorted by HGMTs is given in Figure 3-3. Most frequently noted were radicell peat, amorphous peat and colluvial substrate high in OM. Gyttja substrates were only found in site ID1-ID3 and UVB. Wood peat and wood-radicell peat were exclusively encountered in sites UVB and CVB. Ficus peat was merely found in site UVB, although an occurrence in channelled valley-bottoms is also likely as *Ficus trichopoda* appears patchwise in homogeneous stands in peat swamp forests of channelled valley-bottoms (Grobler 2009). Raphia peat was exclusively recognised in site FP, whereas alluvial loam was only found in site CVB.

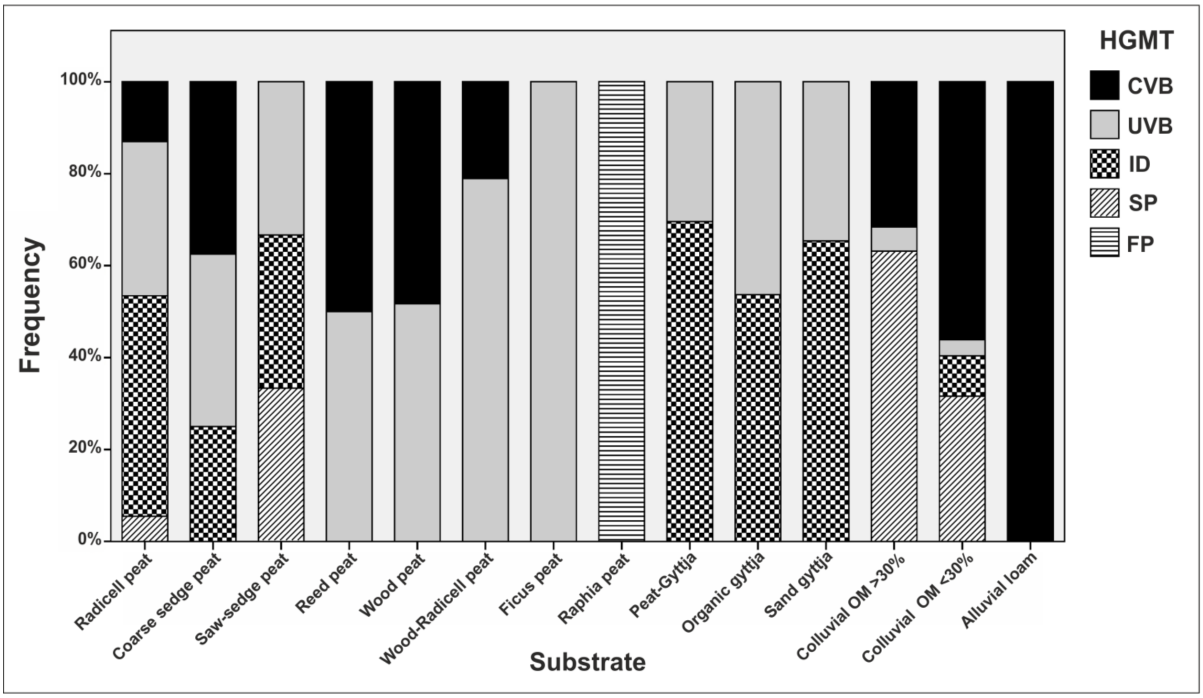


Figure 3-3: Frequency of substrate occurrence per HGMT (100%=total number of horizons of a substrate). CVB=Channelled valley-bottom; FP=Flood plain; ID=Interdune depression; SP=Seep; UVB=Unchannelled valley-bottom.

Vice versa, the percentage occurrence of the different substrates at each HGMT is given in Table 3-7 (as a weighted percentage according to the vertical extent). Amorphous peat as a product of human activities was excluded from this consideration. Site CVB is dominated by wood peat, usually with underlaying colluvial organic substrate high in OM (Supplementary Material 1). Alluvial loam occurs in various places in the cross sections, predominantly at the fringes.

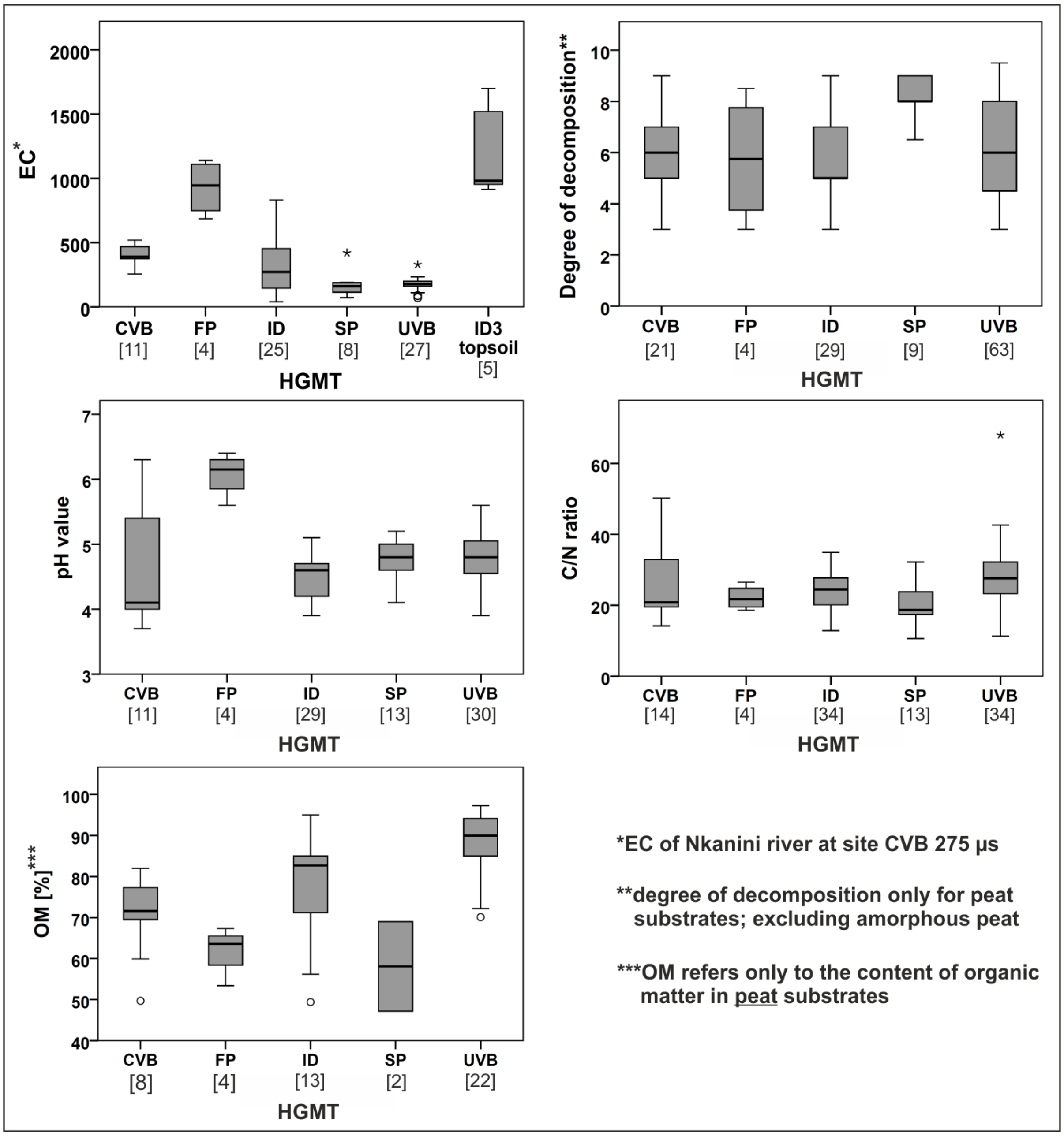
At site FP, raphia peat was the only described substrate. This is due to the fact that the characterisation raphia peat was, as mentioned, a special research target. In sites ID1-ID3 organic gyttja is the most prominent substrate, chronologically occurring in succession after sand gyttja and before peat-gyttja and radicell peat (Supplementary Material 2-4). In site SP colluvial organic substrate low in OM is the dominant substrate usually occurring as a thick base layer (Supplementary 5). Second most common is colluvial organic substrate high in OM that usually forms the overlying layer; itself being covered by a topsoil layer of radicell peat. Unchannelled valley-bottoms are the most diverse HGMT, dominated by organic gyttja in the profound layers (Supplementary Material 6-8). Wood peat, radicell peat and wood-radicell peat were found in almost equal shares; the latter mostly in the upper layers of disturbed transects (Supplementary Material 6 and 7).

Table 3-7: Occurrence of substrates, weighted by vertical extent, for each HGMT. Amorphous peat was excluded as it mostly reflects the human impact and not a natural distribution. CVB=Channelled valley-bottom; FP=Flood plain; ID=Interdune depression; SP=Seep; UVB= Unchannelled valley-bottom.

Substrates\HGMTs	CVB	FP	ID	SP	UVB
Radicell peat	7.5%	-	17.2%	9.9%	18.2%
Coarse sedge peat	1.6%	-	0.3%	-	0.8%
Saw-sedge peat	-	-	0.1%	0.9%	0.2%
Reed peat	2.5%	-	-	-	0.7%
Wood peat	35.7%	-	-	-	16.7%
Wood-Radicell peat	7.2%	-	-	-	18.3%
Ficus peat	-	-	-	-	0.6%
Raphia peat	-	100.0%	-	-	-
Peat-Gyttja	-	-	19.6%	-	9.0%
Organic gyttja	-	-	45.6%	-	25.3%
Sand gyttja	-	-	16.6%	-	9.4%
Colluvial > OM	5.6%	-	-	21.9%	0.2%
Colluvial < OM	22.7%	-	0.7%	67.2%	0.6%
Alluvial loam	17.2%	-	-	-	-

As the topsoils of the non-pristine sites were subject to mineralisation and compaction, their vertical extent may have been greater before human interference. Wood peat in sites UVB and CVB, and radicell peat in site ID are undervalued, as they are the main formed substrates under current climate conditions.

The determined physical-chemical characteristics of the different HGMTs are depicted in Figure 3-4. The electric conductivity is generally between 180 and 400 µS/cm except for site FP and the topsoil of site ID3, where it is much higher. The mean degree of peat decomposition for all HGMTs is around H6, except for SP, where higher degrees around H8 prevail. All HGMTs have low pH values between four and five, except for FP, where the pH value is around six. The mean C/N ratios for all HGMTs range from 20 to 29. The organic matter content in peat is highest for UVB and ID, the latter though, with a greater variation. The lowest organic matter content in peat is found in SP.



*EC of Nkanini river at site CVB 275 µs

**degree of decomposition only for peat substrates; excluding amorphous peat

***OM refers only to the content of organic matter in peat substrates

Figure 3-4: Characteristics according to HGMTs. Sample number in brackets [N]. CVB=Channelled valley-bottom; FP=Flood plain; ID=Interdune depression; SP=Seep; UVB=Unchannelled valley-bottom.

3.5 Discussion

3.5.1 Substrate's characteristics

Radicell peat is the most frequently encountered peat type, usually in a medium degree of decomposition around H6. It has a surprisingly low mean content of organic matter (75%), which seems contradictory to the considerably low bulk density of 0.12 g/cm³ and suggests that the SOM/SOC conversion factor of 1.88 by Farmer et al. (2014) might be too low for this substrate type. In addition, the typical intermixtures of gyttja presumably lower the organic matter content as well.

Coarse sedge peat has very high organic matter contents, a medium degree of decomposition and bulk densities amongst the lowest of all substrates. This points toward relatively constant anaerobic conditions, probably to peat formation in shallow water. Additionally, small intermixtures of organic gyttja may elevate the degree of decomposition according to von Post (1922).

Saw-sedge peat shows characteristics similar to coarse sedge peat. It is liable to form in shallow water, where organic gyttja intermixtures may also be found. Further, it has a high C/N ratio of 41.

Reed peat was a rare substrate in our research and always found to have a relatively low degree of decomposition (H4-H5). It was not investigated further and requires future research.

Wood peat is a common substrate with considerably high mean contents of organic matter (82.2%) and mean degree of decomposition around H6. Gabriel et al. (2017) indicate that the relatively high organic matter contents in wood peat can be partly attributed to the fact that peat swamp forests are the only type of mire vegetation in Maputaland, in which natural fire doesn't occur frequently. The total pore volume in wood peat is also very high.

Ficus peat as a subtype of wood peat is the rarest substrate. Nevertheless, it was easily identified due to its unmistakable appearance. It has the highest organic matter contents and lowest degree of decomposition of all substrates and an extremely high C/N ratio of 68.

Wood-Radicell peat is a common substrate, which resembles wood peat in degree of decomposition and organic matter content. Further, it is the substrate with the lowest bulk density (0.09 g/cm^3) and therefore with the greatest pore volume (96.3%).

Raphia peat of different species is known to be an important peat builder in tropical regions, like the Congo Basin (Dargie et al. 2017) or swamps in Panama (Toxler 2007; Hoyos-Santillan et al. 2016), Guinea and Liberia (Bord na Móna 1985). In South Africa it is rare and was not encountered in any HGMT other than the flood plain. Also Smuts (1996) indicated that the palm only occurred on the borders of the Siyadla River and the shores of Lake Amanzimyama. Toxler (2007) mentioned *Raphia taedigera* as a coloniser, initiating peat formation in coastal freshwater swamps. As the roots of *Raphia* palms are pneumathodes they conduct oxygen in water saturated soil, which may enhance peat decomposition as well (Hoyos-Santillan et al. 2016). Its organic matter content is relatively low (62%) and its bulk density the highest among the non-degraded peat substrates, because of continuous input of mineral fluviatile deposits during flood events. Smuts (1996) determined an average organic matter content about 80%, probably at the western shore of Lake Amanzimyama with less pronounced river dynamics. The C/N ratio lies within the range of the other peat substrates, but the pH value measured at the raphia peat site is much higher at 6.1.

Amorphous peat, affected by mineralisation and compaction, has a relatively low mean organic matter content. As an organic substrate, its bulk density is still high. The continued decomposition processes in amorphous peat lead to an increase of NH_4^+ and H^+ and therefore to a decrease of the C/N ratio and to further acidification (Prévost et al. 1999; Adamson et al. 2000). Hence, we find the lowest values for C/N=19.4 and pH=4.2 in amorphous peat.

Organic gyttja is a common substrate. As a limnic deposit it mostly consists of detritus and therefore organic matter (Succow and Joosten 2001). However, according to the distance to the surrounding dunes as source for mineral intermixtures, the content of organic matter can fluctuate considerably (Gabriel et al. 2017). In general, organic gyttja has a lower organic matter content and higher bulk density than peat substrates, but with a total pore volume which is equally high.

Sand gyttja has by definition a content of organic matter below 30%. The mean bulk density of the recorded samples is therefore quite high (0.63 g/cm³). In contrast to peat substrates the total pore volume is much lower.

Peat-gyttja is a common substrate in interdune depressions and was also encountered in unchannelled valley-bottom sites. It appears to have high von Post (1922) degrees of decomposition H7-H9, because of the amount of squishy gyttja, even though the plant residues are less decomposed. Physically, it therefore resembles peat in higher degrees of decomposition, with lower contents of organic matter than radicell peat and with bulk densities between those of radicell peat and organic gyttja.

Colluvial organic substrate low in OM is usually found at the fringes of peatlands, where continuously deposited sand accumulates alongside not entirely decomposed organic matter from wetland plants. It resembles sand gyttja, but usually has lower contents of organic matter. This is evidence for a faster deposition of sand during the formation of colluvial organic substrates low in OM than during the formation of sand gyttja. Consequently, the total pore volume was the lowest and bulk densities were the highest of all substrates.

Colluvial organic substrate high in OM is an uncommon substrate. It resembles organic gyttja, however, with slightly higher proportions of the mineral fraction.

Alluvial loam rich in OM was rarely encountered. If encountered it generally shows high contents of the mineral fraction, distinctly different to all other substrates is its high content of mineral particles finer than sand.

3.5.2 HGMT characteristics

For almost all HGMTs the mean *electric conductivity* lies between 180 and 400 µS/cm. These values match with those measured by Grobler (2009) in different valley-bottom peatlands in the Kosi Bay region, with a range of between 175 and 430 µS/cm, as well as with the results of Taylor et al. (2006) who measured conductivities between 200 and 400 µS/cm in the groundwater around Lake St. Lucia. The lowest values of this research were found in SP and UVB with 177 and 180 µS/cm, indicating a close influence of rainwater runoff from the surrounding higher lying areas. A higher influence of ion-rich groundwater is expected in the CVB with a mean of 400 µS/cm. The site FP, influenced by the river, has values above 900 µS/cm, suggesting an even greater contribution from groundwater. These results, however, give indications rather than solid proof for the origin of the water and should be ascertained with appropriate tests such as investigations of the water’s macro-ionic composition. A special situation was found in the topsoil (0-50 cm) of site ID3, where values above 1200 µS/cm, were noted and the mean of the subsoil is 410 µS/cm. The values noted in the topsoil are explainable by the lowering of the water table in the area around ID3 (Vazi North) due to *Eucalyptus* and *Pinus* plantations, which lower the local water table considerably (Grundling and Blackmore 1998; Garschhammer et al. 2016). The current water table fluctuates between 0 and 50 cm depth, leading to capillary rise from the saturated stratum underneath and to evaporation from the surface. Soluble salts remain in the topsoil after evaporation increasing the electric conductivity. In addition, the site is used as grazing ground for cattle, increasing the content of electrolytes through urine.

The *degree of peat decomposition* (von Post 1922) with mean values around H6 reveals that Maputaland doesn’t have optimal peat-forming conditions, in contrast to rain fed peatlands in temperate and cold climates, for example, where peat accumulates at low degrees of decomposition (Moore 1989). Even though the relatively low pH values will have a diminishing effect on microbial activity, the warm climate and the pronounced hydroperiods increase peat decomposition (Rydin and Jeglum 2006; Ollis et al. 2013). Frequent surface fires, which occur in all vegetational peatland types except peat swamp forest, also contribute to an increase in peat decomposition (Gabriel et al. 2017). Highest mean decomposition values are found in seeps, which are neither located in positions where water accumulates, like interdune depressions and unchannelled valley-bottoms, nor do they have a constant water input from aquifers. Therefore, they rapidly dry when water tables drop after the rainy season and have longer aerobic periods than other HGMTs. Mature peat swamp forest, which cover channelled and unchannelled valley-bottoms, accumulate peat with the lowest degrees of decomposition.

There are two factors that have an important influence on the substrate’s *organic matter contents*. First is the seasonally influenced consistency of water saturation and second the transport of mineral particles into the substrate. Mineralisation of organic matter has a greater impact when water saturation is not consistent, as for example in floodplains and seeps. The second factor, sediment input, can be distinguished in two processes namely mineral input of fluviatile sediments (present in channelled valley-bottoms and floodplains) and mineral input of gravitational-deposits (prominent in seeps). Further, with increasing distance to the sediment source (sand dunes), the sand intermixtures are declining as well. The range of organic matter content in the interdune depressions is great. Site ID1 is small and has a lot of sand from the surrounding dunes intermixed into the substrate, while site ID3 has a greater diameter and fewer sand inputs. Site UVB, affected by low water table fluctuations (Gabriel et al. 2017) and a greater diameter, has the highest organic matter contents.

3.5.3 Ecological mire types

According to the classification of *ecological mire types* (Succow and Joosten 2001), all the investigated sites are classed as mesotrophic-acid with a C/N ratio between 20 and 33, and a pH below 4.8 (when adjusted to the KCl pH determination). For non ombrogenic peatlands, the pH values are quite low and certainly related to the leached sands, forming the cover stratum of the lower part of the Maputaland Coastal Plain (Maud 1980; Rydin and Jeglum 2006). The only exception is site FP as a mesotrophic-subneutral mire with a C/N ratio between 20 and 33 and a pH-value between 4.8 and 6.4.

Because the trophic conditions and pH of the study sites are so similar, they do not suit for further differentiation of the substrates under a defined ecological mire type. Only raphia peat was encountered in subneutral conditions. However, due to a lack of reference sites, it is not possible to say if this is the norm or an exception.

In an international comparison, one detail is striking. Where in temperate and cold regions mosses are amongst the dominant peat building vegetation in oligotrophic and mesotrophic mires (Moore 1989; Joosten and Clarke 2002) they are absent in this study.

3.5.4 Substrate reference scheme

The 15 substrates found are classified into the three peatland substrate groups: *gyttja*, *peat* and *organic-mineral deposits* (Figure 3-5). Further, on an intermediate level, a substrate type is defined and on the lowest level a substrate subtype, which refers in the case of peat to the main botanical peat composer. Two substrates, *peat-gyttja* and *sand gyttja,* share characteristics of two peatland substrate groups and are therefore considered as mixed types. *Wood-radicell peat* as a mixture of herbal and wood peat is separated as well.

As the ecological mire type designation did not yield an explanation for the distribution of substrates, it was not included in the classification scheme. However, a differentiation of rare or common occurrence of a substrate within a certain HGMT was considered.

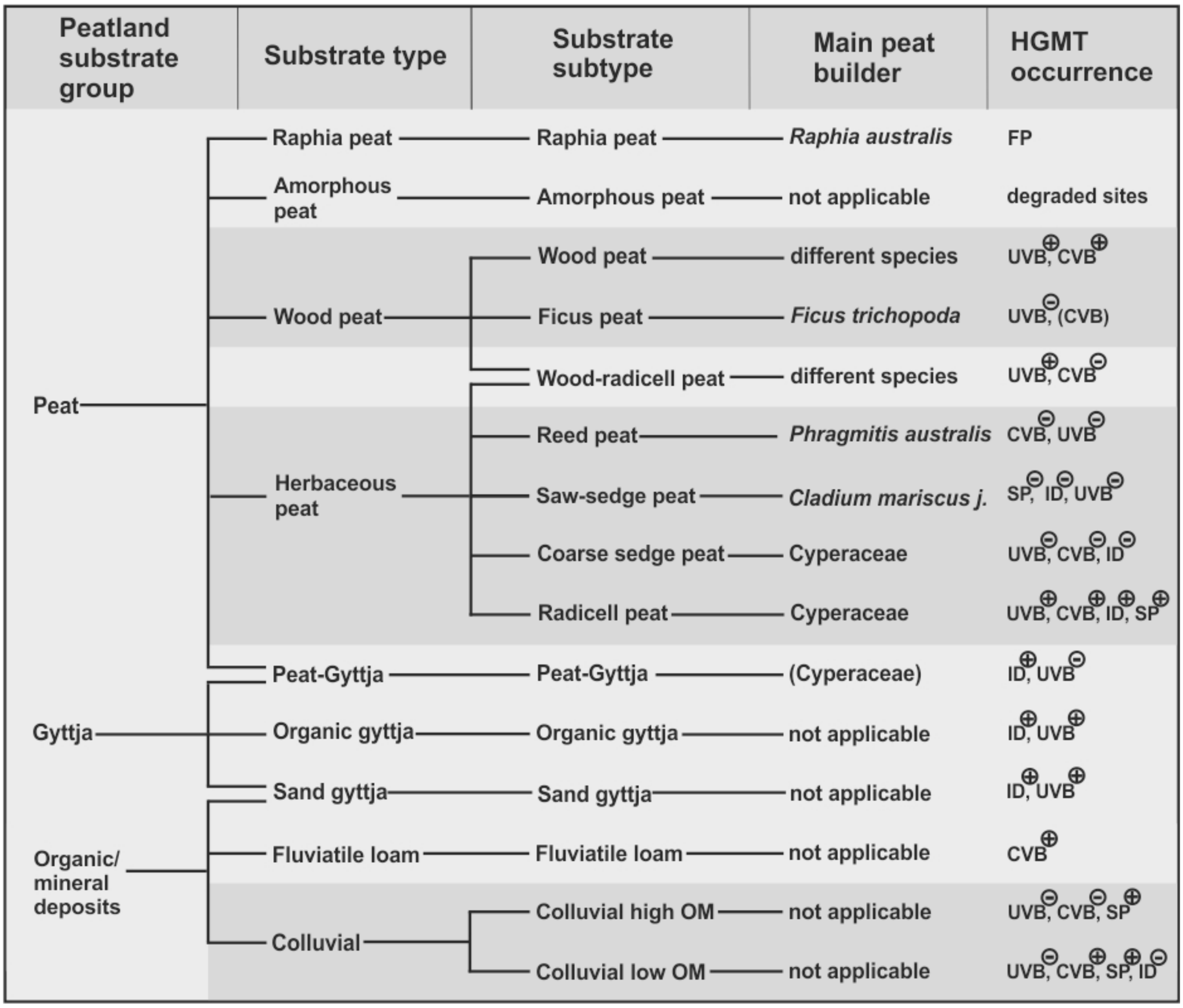


Figure 3-5: Substrate reference scheme. The in HGMT occurrence means rare occurrence, the means common occurrence. CVB=Channelled valley-bottom; FP=Flood plain; ID=Interdune depression; SP=Seep; UVB=Unchannelled valley-bottom.

The results presented here obviously do not reflect the entirety of South African peat substrates, because the study is limited to individual sites on the Maputaland Coastal Plain. For example, Grundling and Grobler (2005) refer to *Cyperus papyrus* as one of the dominant species in the Mkuze swamp, whereas Joosten and Clarke (2002) name it as peat building species. Sieben (2012) further mention palmiet (*Prionium serratum*) forming peat in many of the sandy river valleys in the Eastern Cape Province. *Sphagnum truncatum,* mentioned by Sieben et al. (2016), should also be considered. Other substrate subtypes can easily be included with the application of the principles presented here (main botanical peat builder).

3.6 Conclusions

In general, the strongly seasonal climate in the examined region only allows the formation of peat substrates in a medium degree of decomposition around H6. Because of the very mobile cover sands on the Maputaland Coastal Plain, mineral contents can be high in narrow peatlands surrounded by dunes, thus lowering the organic matter content, the total pore volume and increasing the bulk density. This is especially characteristic for seep substrates. Flood plain and channelled valley-bottom peatlands are also prone to contain fluviatile mineral inputs.

Ecological mire types turned out to be not useful as a further distinction of peatland types, as no differences were found during this study. When considering peatlands in other regions of South Africa, it might, however, prove to be a valid tool. Only amorphous peat as the top layer of degraded sites has lower pH values and a eutrophic C/N ratio. Differences in the composition of succession vegetation can be expected and display an interesting field for further research.

The proposed substrate reference scheme, together with the morphological description, enables a more precise determination of peatland substrates for the Maputaland Coastal Plain. Further, the physical-chemical characteristics of the substrates yield a basis for the estimation of landscape ecological parameters and eco-functions. Still, this scheme needs to be extended and enriched with other peatland substrates of South Africa.

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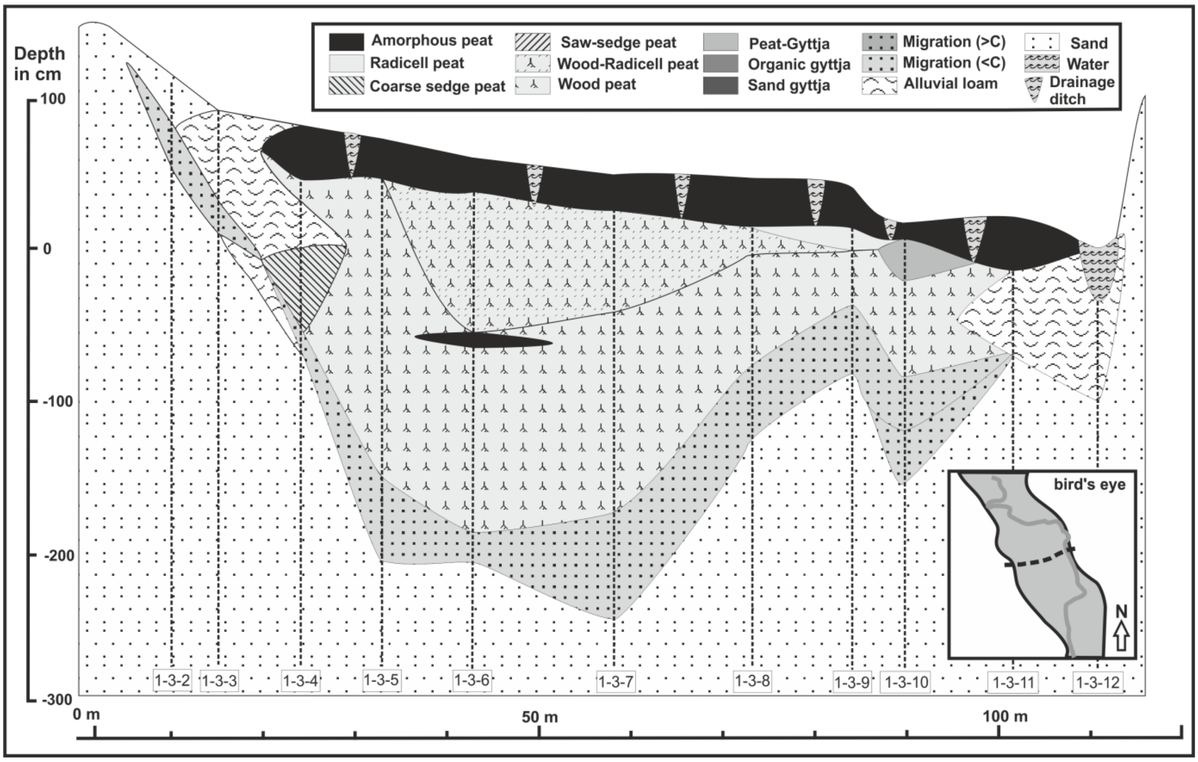
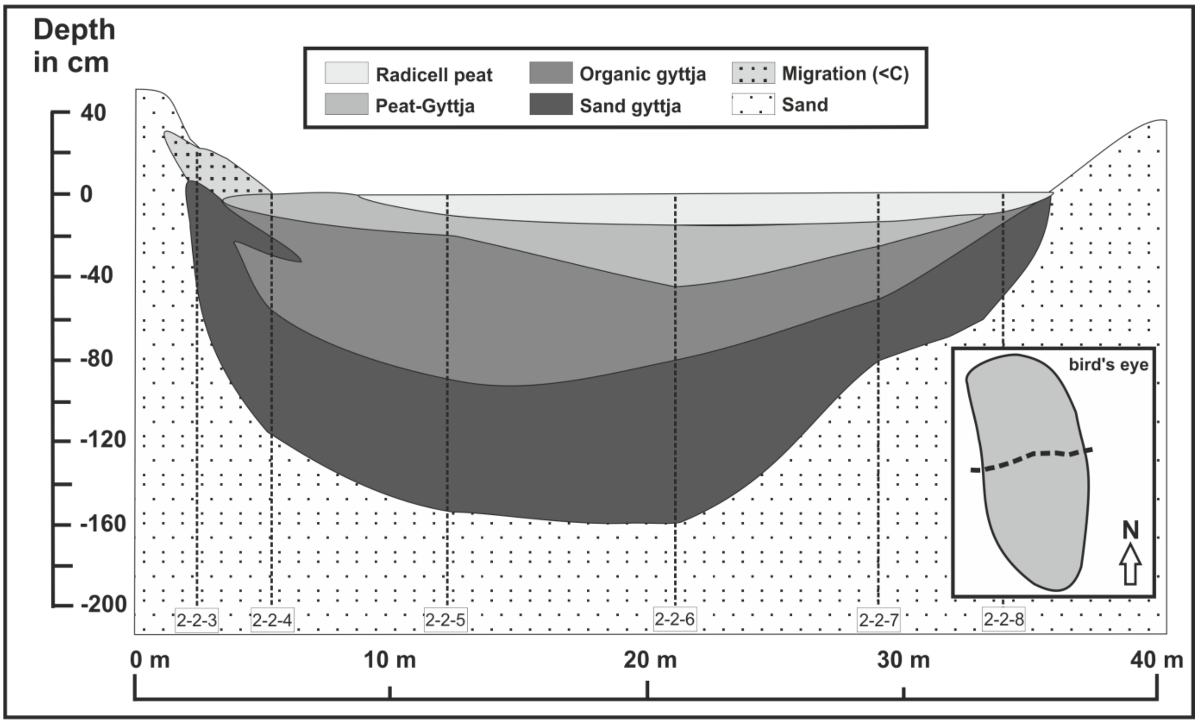
3.9 Supplementary Material



Supplementary Material 1: Cross section site CVB.



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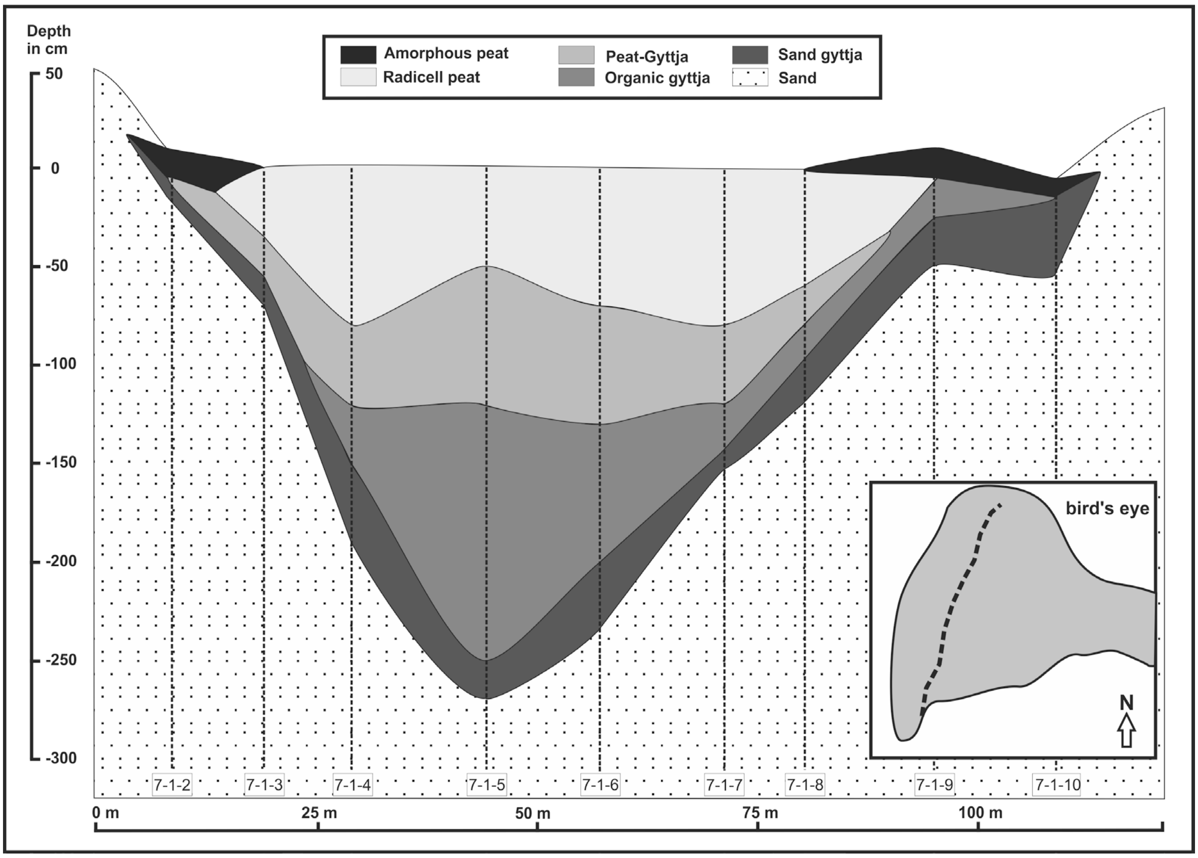

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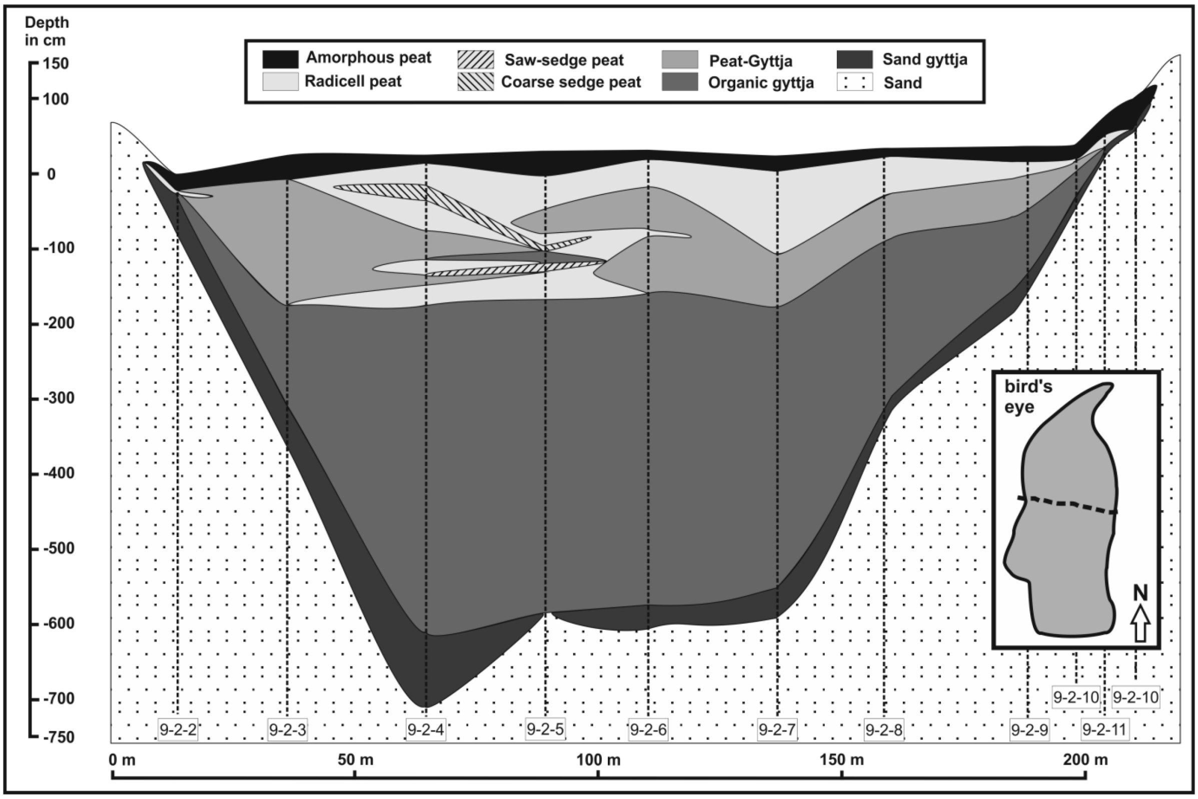

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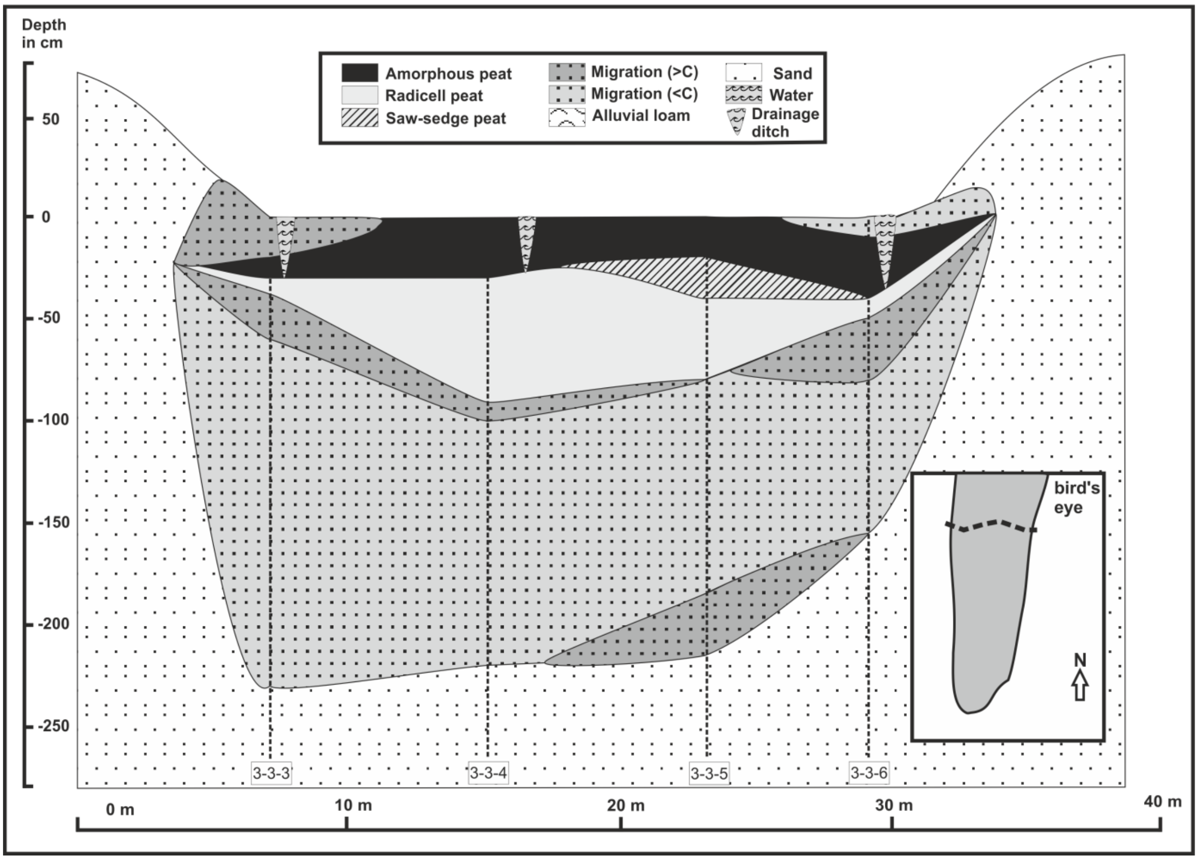

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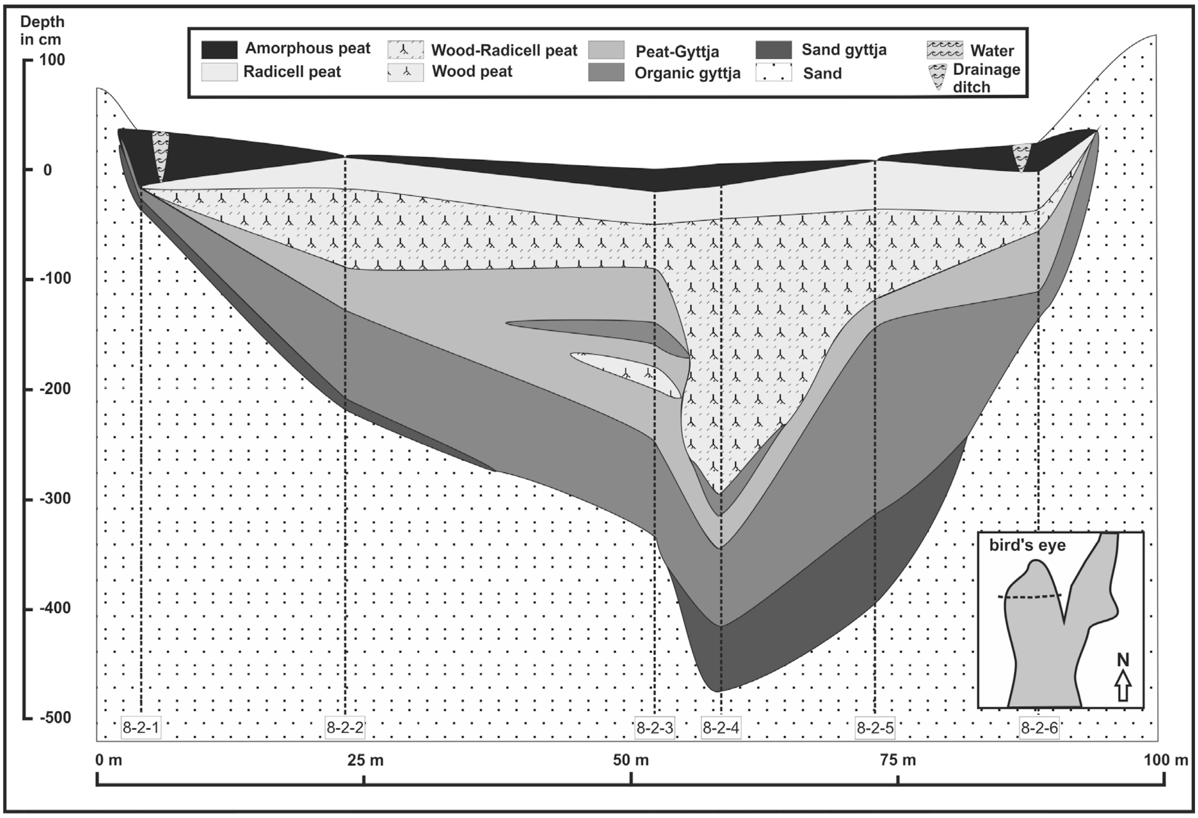
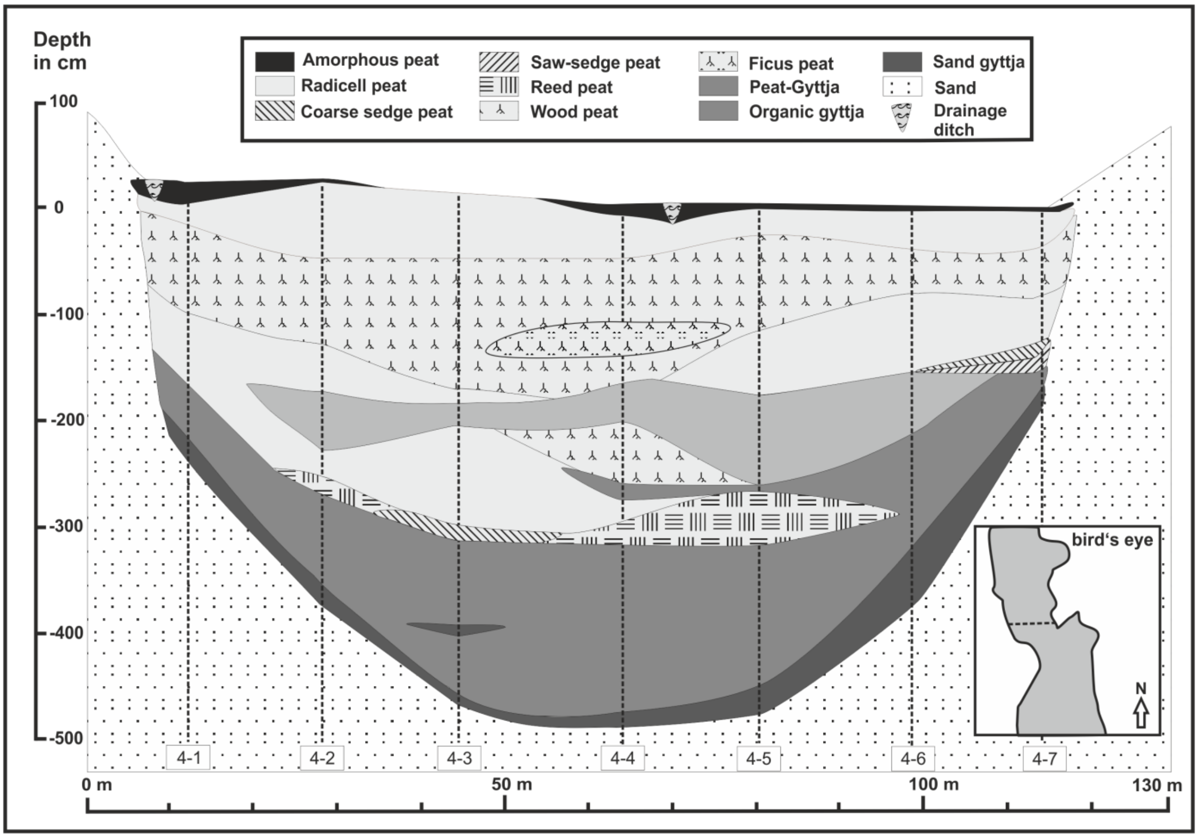
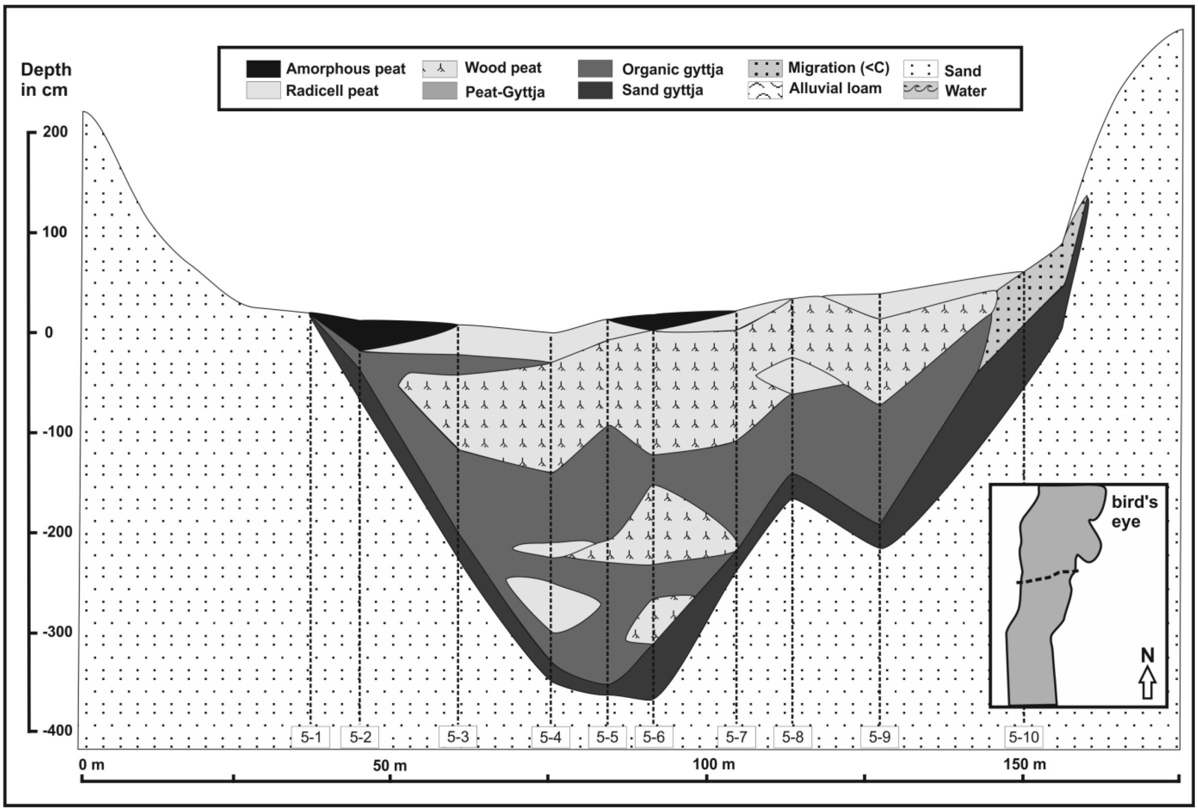


Supplementary Material 6: Cross section site UVB (upper valley).



Supplementary Material 7: Cross section site UVB (middle valley).



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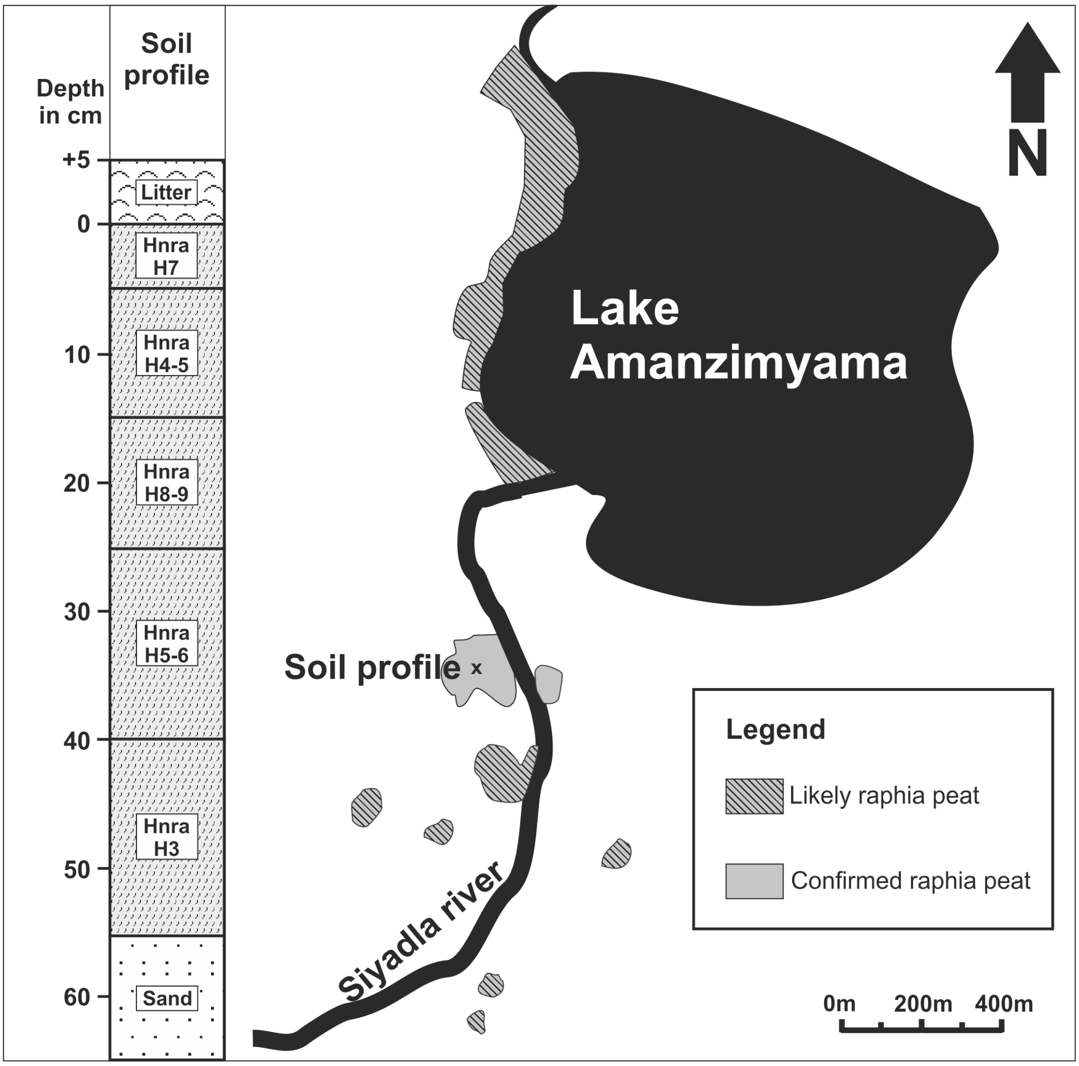

Supplementary Material 9: Soil profile and map of site FP. Likely raphia peat areas, derived from *Raphia australis* vegetation cover, identifiable in satelite image.

4 Physical and hydrological properties of peat as proxies for degradation of South African peatlands – Implications for conservation

Marvin Gabriel[1], Camelia Toader[2], Franziska Faul[3], Niko Roßkopf[1], Piet-Louis Grundling[4,5], Cornie van Huyssteen[6], Althea Grundling[7,8] & Jutta Zeitz[1]

[1] Faculty of Life Science, Humboldt-Universität zu Berlin, Germany

[2] Faculty of Mathematics and Natural Sciences, Humboldt-Universität zu Berlin, Germany

[3] Faculty of Earth and Environmental Sciences, University of Potsdam, Potsdam, Germany

[4] Centre for Environmental management, University of the Free State, Bloemfontein, South Africa

[5] Working for Wetlands, NRMP, Department of Environmental Affairs, Pretoria, South Africa

[6] Department of Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein, South Africa

[7] Agricultural Research Council - Institute for Soil, Climate and Water, Private Bag X79, Pretoria, South Africa

[8] Applied Behavioral Ecology and Ecosystem Research Unit, University of South Africa, Pretoria, South Africa

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Summary

Seven peatlands in northern Maputaland were investigated for the physical and hydrological properties of their substrates. The selected peatlands are representative of typical hydrogeomorphic settings and different stages of human impact, from pristine to severely degraded. Nineteen transects were examined with altogether 141 soil corings to explore typical peatland substrates of the distinct hydrogeomorphic settings. We studied the degree of peat decomposition, organic matter content, bulk density, water retention, saturated hydraulic conductivity and hydrophobicity of the substrates and related them to the degradation processes of peatlands in different hydrogeomorphic settings. Based on these parameters, we also determined the pore size distribution, unsaturated hydraulic conductivity and maximum capillary rise. We found out that after drainage, degradation advances faster in peatlands containing wood peat than in peatlands containing radicell peat. *Eucalyptus* plantations in catchment areas are especially threatening to peatlands in seeps, interdune depressions and unchannelled valley-bottoms. All peatlands and their recharge areas require wise management, especially peat swamp forests in valley-bottoms. Blocking drainage ditches as a first step of restoration of drained peatland areas is indispensable. It might be necessary to enhance the distribution of water into restoration peatlands with further measures. The sensitive peat swamp forest ecosystems should be given conservation priorities.

Keywords: Peat swamp forest, unsaturated hydraulic conductivity, saturated hydraulic conductivity, moorsh forming process, restoration

4.1 Introduction

Peatlands in South Africa are important and threatened ecosystems (Grundling & Grobler 2005, Grundling et al. 2017). Their degradation as a consequence of land use is a common feature (Grundling et al. 2016). Degradation results from the drawdown of the local water tables due to *Eucalyptus* plantations, as well as cultivation practices like drainage, which expose the top peat layers to aerobic conditions (Grundling & Blackmore 1998, Grundling et al. 2016, Pretorius et al. 2014, von Roeder 2015). Aerobic conditions lead to secondary soil formation in peat, i.e. the formation of horizons characterised by compaction and mineralisation, accompanied by alterations of peat structure and also its physical and chemical properties (Schwärzel 2000, Zeitz & Velty 2002, Ilnicki & Zeitz 2003). Further, it is known that peat compaction and mineralisation lead to a shift of the pore size distribution (Ilnicki & Zeitz 2003), alterations of the substrate’s water repellency (Szajdak & Szatyłowics 2010), and a decrease in total porosity (Kecharvarzi et al. 2010), saturated hydraulic conductivity (Kecharvarzi et al. 2010) and carbon content (Ilnicki & Zeitz 2003). These soil properties are important regulators for water movements such as lateral flow, infiltration and capillary rise, and also for water storage capacity and carbon sequestration (Rycroft et al. 1975, Joosten and Clarke 2002). As a consequence of the changes of these soil properties, peatland surface oscillation, a natural mechanism mitigating the topsoil exposure to aerobic conditions during water table fluctuations, is reduced (Whittington & Price 2006). The reduced capacity of a peatland’s surface to oscillate initiates a positive feedback loop, where water table fluctuations further increase and advance the changes of these regulating soil properties (Whittington & Prices 2006). For temperate and boreal peatlands of the northern hemisphere, the influence of degradation on physical soil properties has been extensively studied (Zeitz & Velty 2002, Ilnicki & Zeitz 2003, Zeitz 2003, Whittington & Price 2006). However, for South African peatlands, the degradation impacts are rather unstudied.

Few qualitative studies with a focus on peat properties have been conducted in South Africa. Smuts (1996) was the first to analyse carbon content and sequestration for different South African peat types, with the objective of exploring its value as biofuel. This idea was soon ruled out, as the accumulation rate of about 1 mm does not allow long-term sustainable use (Grundling et al. 2000). Grundling et al. (1998) investigated many of Maputaland's peatlands, including analyses of water holding capacity and ash contents of peatland substrates. In conclusion Grundling et al. (1998) highlighted the peatlands' function as water reservoirs. Except for the deterioration of the Vazi peatland complex, where *Pinus* plantations caused groundwater deficiency and led to severe destruction through peat fires (Grundling & Blackmore 1998), no further investigations into soil degradation of peatlands were realised for a long time.

Faul et al. (2016) investigated physical soil properties for six sites in northern Maputaland. A distinction between pristine peatland substrates and amorphous surface peat of degraded sites was done as well. Their results show that pedogenetically altered peat from degraded sites has a decreased volume of macropores, saturated hydraulic conductivity, hydrophobicity and carbon content, and further a higher bulk density. Against this background, a closer investigation of the effects of degradation of peatlands is needed, including the contemplation of different degradation stages and the consideration of the different peatland types.

The objective of our research is to investigate the effects of drainage on the soil properties of peatlands in different hydrogeomorphic wetland types, in order to identify type-specific threats and to derive implications for conservation, cultivation and restoration (e.g. rewetting).

4.2 Materials and Methods

The study was conducted in the northeastern part of the KwaZulu-Natal province, South Africa. The study area, the northern part of the Maputaland Coastal Plain (Figure 4-1), consists of undulating dunes, with a top layer of wind-redistributed sand of Holocene origin (Maud 1980, Botha & Porat 2007). The climate is subtropical-tropical with mean monthly temperatures between 26°C in February and 17°C in June (Lubbe 1997; Maud 1980). The annual precipitation is about 950 mm and the potential evapotranspiration reaches 2200 mm per annum (Lubbe 1997, Schulze 1997). As the evapotranspiration is higher than the precipitation, peat formation is generally related to groundwater and certain landscape settings (Grundling et al. 2013, Grundling et al. 2016), referred to as hydrogeomorphic wetland types (HGMT). Five HGMTs are found on the Maputaland Coastal

Plain, namely channelled valley-bottom (CVB), unchannelled valley-bottom (UCVB), interdune depression (ID), seep (SP) and floodplain (FP) (Grundling 2014). The first three types are the most common (Grundling 2014, Gabriel et al. 2017b). Each type provides different hydro-ecological conditions and is inhabited by specialised vegetation-communities, which consequently leads to the formation of different botanical peat types (Gabriel et al. 2017b). Different types of gyttja also occur in these systems in addition to peat, and therefore the term *peatland substrates* is used, referring to the entirety of the investigated high organic matter substrates of this study.

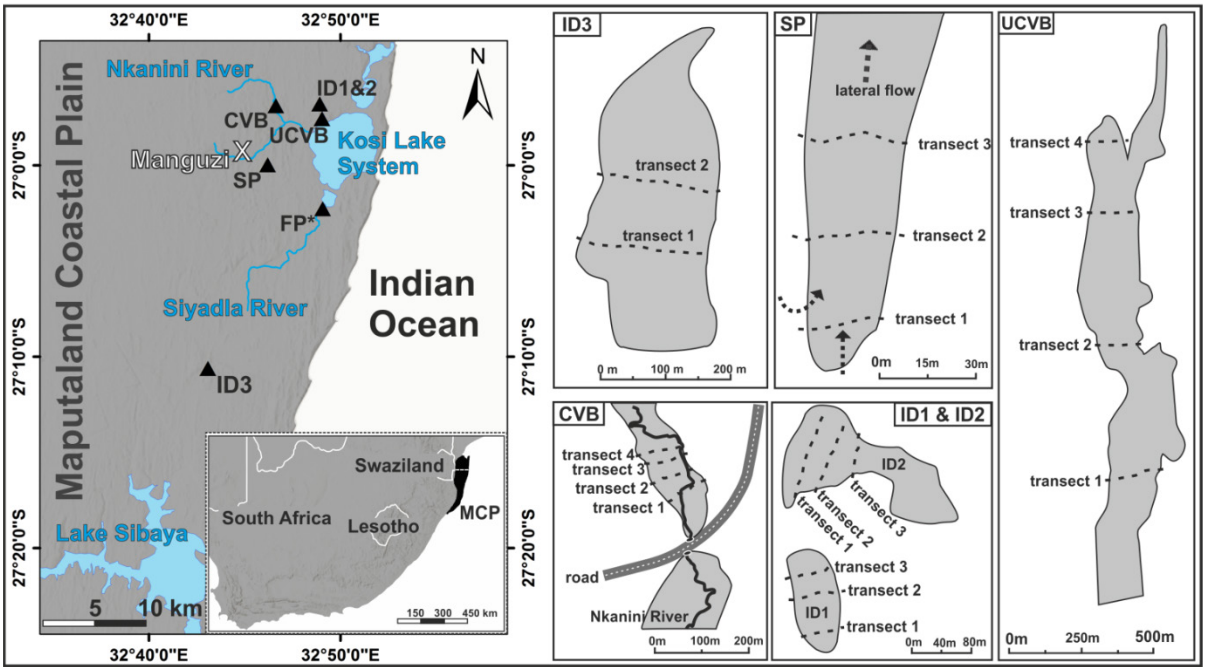


Figure 4-1: Left: Map of the study area around the Kosi Lake System. Right: Individual shape of studied peatlands with indication of transects. Site FP was only investigated in one profile and is therefore not depicted.

Substrate stratigraphies of the peatlands were analysed in transects, creating soil profiles in regular intervals along a linear direction through the peatland. At least one study site was placed at each hydrogeomorphic wetland type (Table 4.1). Interdune depression, unchannelled valley-bottom and channelled valley-bottom as the more common types were investigated in greater detail and each of them at least at one site, affected by degradation due to drainage and cultivation (in CVB, UCVB) or plantations and cattle herding (in ID). The rare type floodplain was not investigated along an entire transect, but only at a single soil profile in order to study the botanically special raphia peat, a peat type formed out of the pneumathodes of the palm *Raphia australis.*

Table 4-1: Overview of study sites and transects.

Site name	Hydrogeomorphic wetland type (HGMT)	Local name	Local name/ coordinates	Size (ha)	Condition; Use	Number of Transects	Number of Profiles
ID1	Interdune depression	KwaMazambane	26°56'52.50"S 32°48'54.57"E	0.2	Centre pristine; cultivation at fringe	3	17
ID2	Interdune depression	eMdoni	26°56'46.81"S 32°48'54.14"E	1.4	Centre pristine; cultivation at fringe	3	22
ID3	Interdune depression	Vazi North	27°10'39.58"S 32°43'3.83"E	15.0	Degraded; cattle herding, surrounded by *Eucalyptus* plantations	2	20
UCVB	Unchannelled valley-bottom	Matitimani	26°57'21.50"S 32°48'59.83"E	38.6	Transects a-c: Succession; - Transect d: Pristine, not used	4	31
CVB	Channelled valley-bottom	Nkanini River	26°56'52.89"S 32°46'37.99"E	2.0*	Succession; no use	4	39
SP	Seep	Nkatwini	26°59'58.23"S 32°46'12.57"E	0.2	Superficially drained; cultivation	3	11
FP	Floodplain	Siyadla River	27° 2'16.83"S 32°49'3.19"E	2-3*	Pristine, not used	0	1

The soil corings were conducted with a Russian peat corer (manufacturer: Eijkelkamp), extracting half-cylindrical cores of 50 cm length and 5.2 cm diameter. Each coring was accompanied by a field soil description based on the German Soil Mapping Directive “KA 5” (Ad-Hoc AG Boden 2005) and according to the botanical peat types identified by Gabriel et al. (2017b). Special focus was given to horizons with secondary soil formation, where aerobic conditions changed the structure and qualities of the drained peat layers. Following the drainage of a pristine mire, a series of chronological soil formation processes is initiated, known as moorsh forming process (Ilnicki & Zeitz 2003). It starts with the formation of a peat shrinkage horizon, evolving into a peat aggregation horizon, evolving into an earthification horizon, terminating as a grainy moorsh horizon (Table 4-2). Moorsh is the end-product of this formation process: a mineralised peat soil with small-grained structure. In this article, degradation will be debated alongside these definitions, while each horizon signals a different degradation stage.

Table 4-2: Horizons of the moorsh forming process (adapted from: Ilnicki & Zeitz 2003; Ad-hoc-AG Boden, 2005).

Horizon	Description	Qualifier (in this study)
Peat shrinkage horizon	Subsoil horizon of drained peatlands, usually directly in transition to non-degraded peat. Oxidation of organic matter and subsidence. Beginning formation of soil structure, vertical cracks.	(shrin.)
Aggregation horizon	Subsoil horizon of drained peatlands. Formation of soil aggregates due to shrinking and swelling; coarse to fine-angular blocky structure, vertical and horizontal shrinkage cracks.	(aggr.)
Earthification horizon	Topsoil horizon of drained peatlands, due to mineralisation and humification formation of crumby, fine-polyhedral to granular soil structure.	(eart.)
Grainy moorsh horizon	Topsoil horizon of drained peatlands, mostly with intensive tillage action; very fine granular to dusty structure, hard and dry.	(moor.)

Subsequent to the transect corings, one profile per transect was chosen as a site-characteristic profile. Its horizons were sampled and analysed in further detail. An overview of the determined soil-parameters and the applied method is given in Table 4-3. Less common substrates, which were encountered within transect corings, but were missing at the site-characteristic profile, were sampled separately.

Table 4-3: Laboratory and field methods used. LAB = determined in laboratory; Field = determined in field.

Parameter	Method	Reference
Bulk density **(Lab)**	Drying of volumetric samples (48 hours, 105°C)	DIN EN 15934: 2012-11
Organic matter **(Lab)**	Loss on ignition (at 550°C) TruSpec CHN-Analyser	Schulte and Hopkins (1996)
Total nitrogen **(Lab)**	TruSpec CHN-Analyser	Leco (2016)
Saturated hydraulic conductivity *Ksat* **(Lab)** Saturated hydraulic conductivity *Ksat* **(field)**	Falling-Head method Auger hole method	Jury, Gardner & Gardner (1991) DIN 19682-8:2012-07
Water retention **(Lab)**	Hanging water column (until pf 2)	Haines (1930) Durner & Iden (2015)
Potential hydrophobicity **(Lab)**	Water drop penetration time	Doerr (1998)
Degree of decomposition **(Field)**	Squeezing test	von Post (1922)

Carbon contents, determined with a True Spec CHN-Analyser, were converted to organic matter by multiplication with the factor 1.88, as suggested by Farmer et al. (2014) for tropical peat. This simple conversion is possible because the soils are completely free of non-organic carbon (Gabriel et al. 2017b).

Undisturbed samples for physical soil analyses were collected for soil reachable from the surface, using volumetric sample rings with a volume of 83 cm³. Unfortunately, the sampling of undisturbed samples from the brittle earthification horizons was not possible. Saturated hydraulic conductivities were conducted on the undisturbed samples using the falling head method.

Subsequently, these samples were used for water retention analyses. With the results of the residual water contents at distinct pressure levels, water retention curves were modelled by the computer programme RETC (van Genuchten et al. 1991), based on equation (1) from van Genuchten (1980).

$$\theta(h) = \theta_r + \frac{(\theta_s - \theta_r)}{[1+(\alpha h)^n]^m} \qquad \text{equation (1)}$$

Where θ(*h*) = water content at pressure level , θ*s* = water content at saturation, θ*r* = residual water content at permanent wilting point pF 4.2. α and *n* are dimensionless empirical shape parameters related to the pore size distribution and *m* is calculated *m* = 1-(1/*n*).

Afterwards, the samples were dried for 48 hours at 105°C to determine the bulk density. Samples from substrates not reachable from the surface were taken as volumetric sections, cut from the peat cores and were treated in the same way.

Peat substrate types not comprised in the site-characteristic profiles were sampled separately for the determination of saturated hydraulic conductivities and bulk densities. Measurements of water retention could unfortunately not be realised for these samples.

With the values for α, *n* and *m* from equation (1) the unsaturated hydraulic conductivity was calculated according to the *Mualem-van Genuchten model* (equations (2) and (3)) (Mualem 1976, van Genuchten 1980).

$$K_u(S_e) = K_{sat} S_e^l [1 - (1 - S_e^{\frac{1}{m}})^m]^2 \qquad \text{equation (2)}$$

$$S_e(h) = \frac{1}{[1+(\alpha h)^n]^m} \qquad \text{equation (3)}$$

Where K_u = the unsaturated hydraulic conductivity, S_e=the effective saturation and *l* = a dimensionless pore connectivity parameter (estimated by Mualem (1976) =0.5).

Knowing the unsaturated hydraulic conductivity, the maximum capillary rise for a substrate was numerically approximated, using equation (4) by Brandyk et al. (1986).

$$z = \sum_{i=1}^{m} \frac{\Delta h}{1+q/K(h_{avi})} \qquad \text{equation (4)}$$

Where *z* = maximum capillary rise, *m* = number of intervals of equal size, Δ*h* = size intervals, h_{avi} = average pressure head within *i*-th interval = $(h_i+h_{i+1})/2$, and $K(h_{avi})$ = unsaturated conductivity at that pressure head. Size intervals were calculated in steps of Δ*h* = 10 cm until a pressure head of *h* = 16000 cm (water column)

The pore size distribution was derived from the different pressure levels of the water retention experiment. pF 0-1.8 = wide coarse pores (>50 µm) ; pF 1.8-2.5 = narrow coarse pores (50-10 µm); pF 2.5-4.2 = mesopores (10-0.2 µm); > pF 4.2 = fine pores (<0.2 µm), according to Ad-hoc-AG Boden (2005).

For comparison with the laboratory method, saturated conductivities were measured in the field, with the auger hole method (DIN 19682-8:2012-07). This technique relies on the refilling of a perforated tube in a borehole with soil water after emptying it. Values for amorphous peat layers of drained sites could not be obtained, as the tube is only refilled up to the current peatland water table.

4.3 Results

4.3.1 Hydrogeomorphic wetland types and peatland substrates

An overview of the encountered substrates in the different hydrogeomorphic wetlands types is given in Table 4-4. Amorphous peat was commonly encountered close to the surface in drained peatlands. The qualifiers of Table 4-2 are added to distinguish the degree of degradation, i.e. the horizon of the moorsh forming process.

Table 4-4: Frequencies of horizons from a certain substrate at each hydrogeomorphic wetland type (HGMT). CVB = channelled valley-bottom; UCVB = unchannelled valley-bottom; ID = interdune depression; SP = Seep; FP = Floodplain.

Substrate	**Total**	**CVB**	**UCVB**	**ID**	**SP**	**FP***	**Degree of decomp. (range), Ø**
Radicell peat	145	18	49	70	8	-	H3-9, H6
Wood peat	58	28	30	-	-	-	H3-9, H6
Wood-radicell peat	39	9	30	-	-	-	H3-9, H6
Saw-sedge peat	3	-	1	1	1	-	H4-8, H6
Coarse sedge peat	8	3	3	2	-	-	H3-7; H5
Ficus peat	2	-	2	-	-	-	H3-5, H4
Raphia peat	4	-	-	-	-	4	H3-9, H6
Amorphous peat (shrin.)	46	23	11	5	7	-	H9-10, H10
Amorphous peat (aggr.)	36	12	2	19	3	-	H10
Amorphous peat (eart.)	51	14	6	26	5	-	H10
Amorphous peat fossil	4	3	1	-	-	-	H10
Peat-gyttja	68	-	21	47	-	-	n.a.
Organic gyttja	82	-	38	44	-	-	n.a.
Sand gyttja	78	-	27	51	-	-	n.a.

*the indicated number of frequencies doesn't have significance for Flood Plains, because other peatland substrates of this HGMT have been neglected

The most common peat types are radicell peat, wood peat and wood-radicell peat, all with an average degree of decomposition of H6. Wood peat predominates in channelled valley-bottoms, radicell peat in interdune depressions. Unchannelled valley-bottoms have radicell peat, but also wood and wood-radicell peat as predominant substrates. According to Gabriel et al. (2017a) the current sedge-reed vegetation at site UCVB and site CVB are succession communities of cleared swamp forest. Therefore, it must be assumed that wood peat would have had a greater abundance, if these sites were pristine. Gyttja substrates are only encountered in the interdune depressions and the unchannelled valley-bottom site (Gabriel 2017b).

4.3.2 Secondary soil formation

Degradation horizons occurred in several sites. Site ID3, used for cattle herding and surrounded by *Eucalyptus* and *Pinus* plantations, revealed the clearest formation of earthification and aggregation horizons. Intense signs of secondary soil formation were also observed at site CVB, where the maintenance of the drainage channels stopped just a year before the field investigation. The channels were partly blocked by vegetation and eroded peat decomposition products. Site SP was currently used for agriculture. Because of the active drainage the top 30 cm consisted of decomposed amorphous peat, but clear horizonation was not as prominent as at the other sites as a result of tillage. The transects UCVB (1) – UCVB (3) which were in succession after drainage and cultivation spanning a few years, exhibited horizons where radicell peat from sedge-reed vegetation formed within a layer of amorphous peat in the top decimetres.

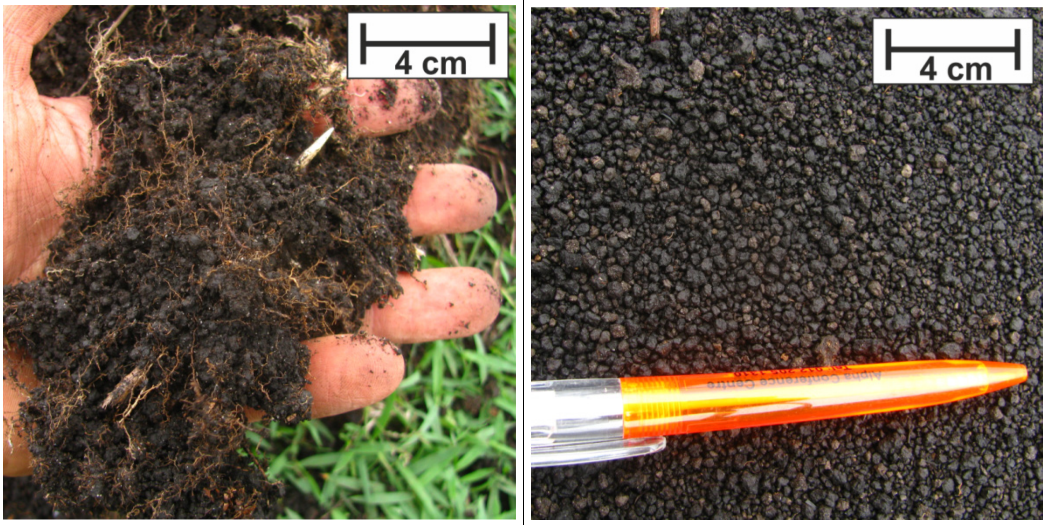
Earthification horizons, extending until 5-10 cm, were the predominant topsoil horizon of degraded sites, usually underneath succeeded by aggregation horizons. Aggregation horizons were encountered until a mean depth of 20 cm. The registered peat shrinkage horizons reached a mean depth of 25 cm. In some cases, clearly developed horizonations of earthification horizons over aggregation horizons over peat shrinkage horizons were identified. In other cases, earthification horizons were located directly over peat shrinkage horizons. Fossil peat degradation horizons were only encountered four times, probably providing evidence of past drought periods. The appearance and structure of each horizon is depicted in Figure 4-2**.**

Peat shrinkage horizon

mean extent: 19 cm
mean lower limit: 25 cm
maximum depth: 50 cm

Aggregation horizon

mean extent: 14 cm
mean lower limit: 20 cm
maximum depth: 40 cm



Earthification horizon

mean extent: 7 cm
mean lower limit: 7 cm
maximum depth: 30 cm

Grainy moorsh horizon*

Not encountered in the transects

*image taken in a small depression with a shallow degraded peat layer close to site ID3

Figure 4-2: Appearance of the structure of degradation horizons.

4.3.3 Organic matter and bulk density

The organic matter contents and the bulk densities of the different substrates are given Figure 4-3.

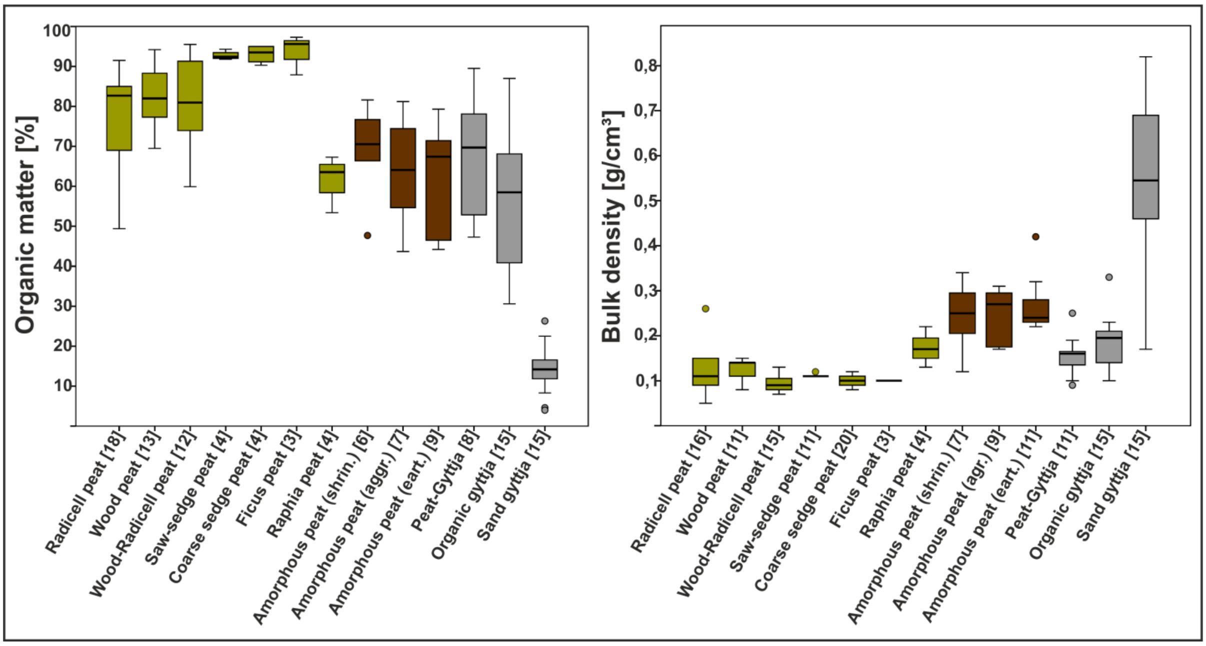


Figure 4-3: Boxplots of organic matter content and bulk density for each substrate. Boxes with greenish colour represent pristine peat substrates; in brown amorphous peat; in grey non-peat substrates.

Pristine peat substrates have high organic matter contents between 70% and 95%, except for raphia peat. Amorphous peat has lower contents between 80% and 50%, decreasing with the degree of degradation. The bulk densities of the pristine peat substrates were 0.1-0.15 g/cm³, except for raphia peat with 0.15-0.2 g/cm³ due to a higher mineral content. Horizons of amorphous peat with 0.2-0.3 g/cm³ were much denser.

4.3.4 Water retention

Water retention curves are depicted in Figure 4-4. Wood peat loses its water content the fastest of the pristine peat substrates, with $\vartheta = 0.94$ at pF 0, $\vartheta = 0.67$ at pF 1.8 and $\vartheta = 0.36$ at pF 4.2. The other pristine peat substrates show similar curves, however maintaining a water content (ϑ) around 0.1 points higher between pF 1.0 and pF 3.0. Amorphous peat (shrin.) shows a curve similar to the ones from pristine peat substrates. Amorphous peat (aggr.) has the lowest water content at pF0 of $\vartheta = 0.89$. Between pF 1.5 and pF 2.0 it surpasses the other peat substrates and has by far the highest residual water content of ϑ=0.54 at the permanent wilting point pF4.2.

Compared to the peat substrates, peat-gyttja show a delayed loss of water or a higher water retention capacity than the pristine peat substrates. Organic gyttja resembles amorphous peat (shrin.) in its water retention characteristics. Sand gyttja has the lowest water retention potential, with $\vartheta = 0.59$ at pF 0 and $\vartheta = 0.28$ at pF 4.2.

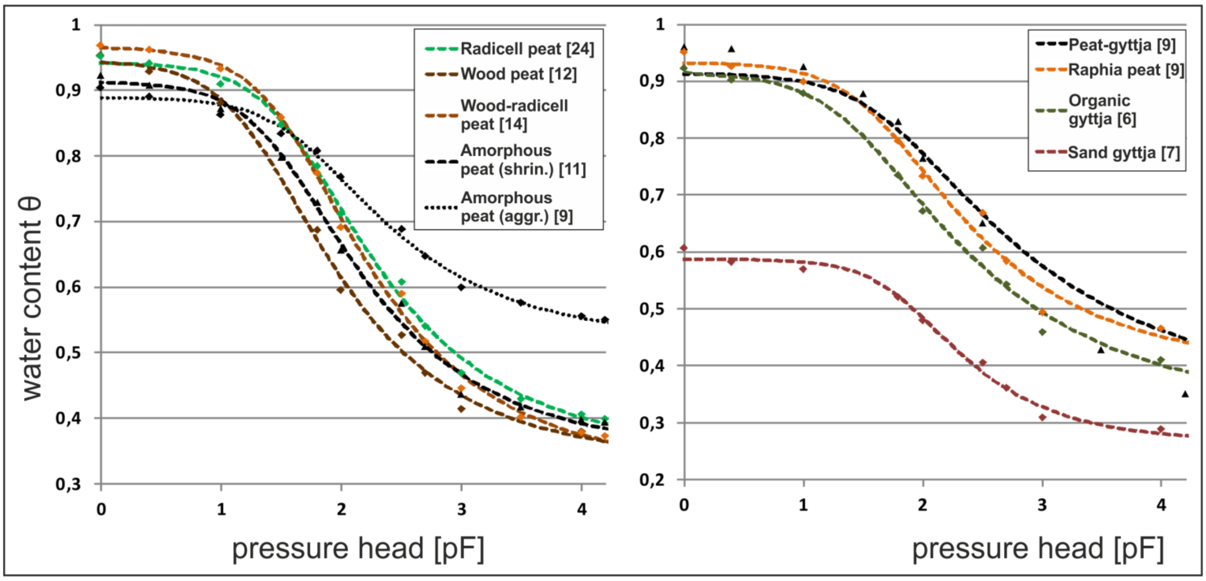


Figure 4-4: Water retention curves for the different peat substrates.

4.3.5 Pore size distribution

The pore size distribution is depicted in Figure 4-5. All substrates, except sand gyttja, have total pore volumes greater than 90%. With 27%, wood peat has the highest fraction of wide coarse pores, whereas with 9.6%, amorphous peat from aggregation horizons the lowest. The volume of narrow coarse pores for all substrates varies between 12% and 18%. Peat-gyttja has a relatively high volume of mesopores with 30%, while the other substrates have fractions between 13% and 23%. With 55%, amorphous peat from aggregation horizons has the highest volume of fine pores.

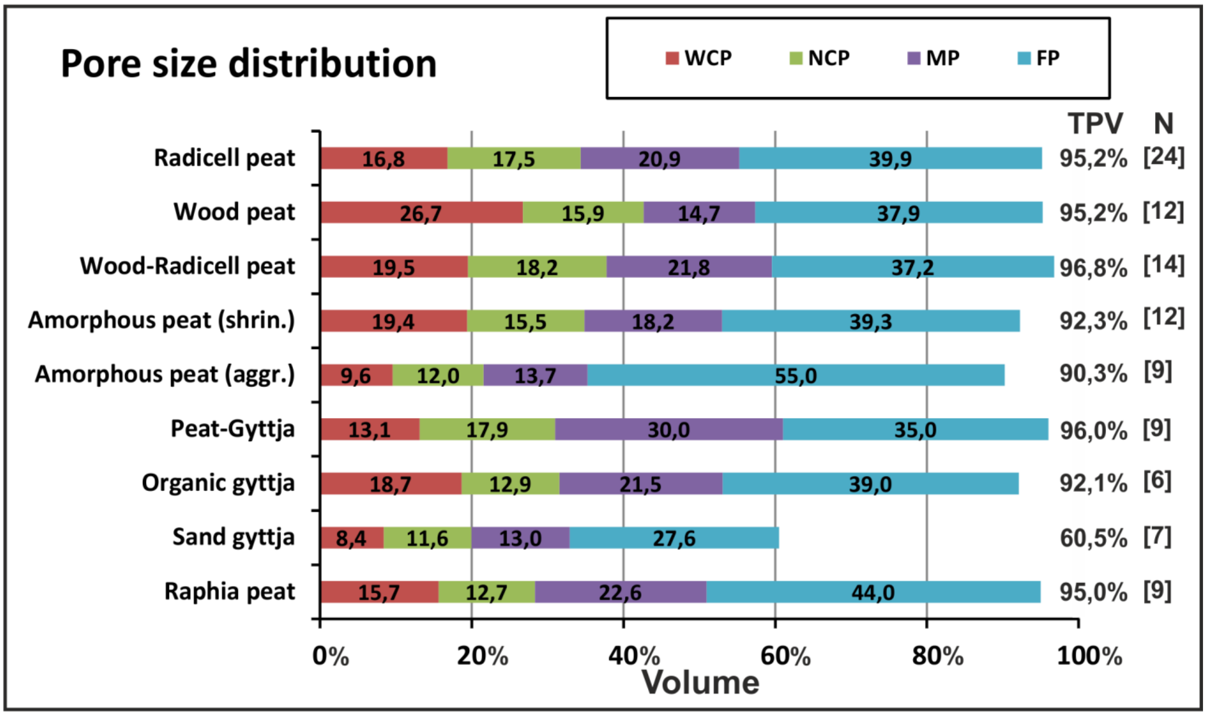


Figure 4-5: Pore size distribution according to each substrate. WCP = wide coarse pores (pF 0-1.8); NCP = narrow coarse pores (pF 1.8-2.5); MP = mesopores (pF 2.5-4.2); FP = fine pores (> pF 4.2); TPV = total pore volume; N = sample size.

4.3.6 Saturated hydraulic conductivity

There is a great variation in saturated hydraulic conductivity (K_{sat}) between different peatland substrates, and partly among different samples of the same substrate. Figure 4-6 visualises the measured K_{sat}-values. Exceeding the depth limit of the auger hole method, no borehole measurements could be determined for coarse sedge peat, saw-sedge peat and Ficus peat. Further, this method was not applicable for unsaturated horizons, hence for the degradation horizons.

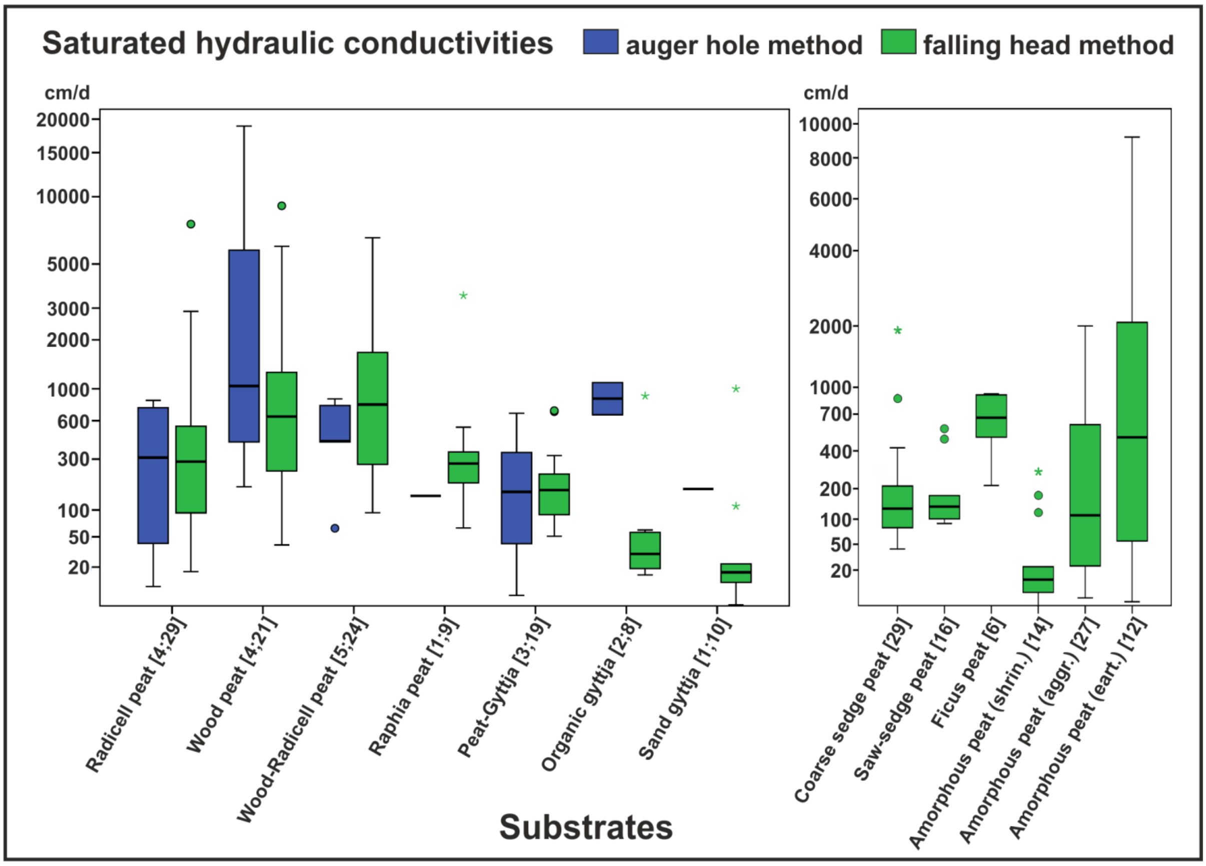


Figure 4-6: Saturated hydraulic conductivities (Ksat) for different peatland substrates. X-axis with substrates and sample size in brackets. Left = Ksat-values for substrates measured in laboratory and field; right = Ksat-values for substrates only measured in laboratory.

The peat substrates have higher K_{sat}-values than the non-peat substrates. Wood peat shows the highest K_{sat}-values and also the greatest spread. Even though most previous laboratory determined values lie between 300 and 1000 cm/day, extreme values up to 10 000 cm/day were measured in our lab. Field measurements yielded even higher values with a median of around 1000 cm/day and an extreme of 18 600 cm/day. Field and laboratory values are similar for radicell peat and peat-gyttja, whereas for organic gyttja a considerable difference is observed (field: 880 cm/day, lab:140 cm/day). Saw-sedge peat and coarse-sedge peat have the lowest values of the pristine peat substrate. Among the amorphous peat substrates, an increase from amorphous peat (shrin.) to amorphous peat (aggr.) to amorphous peat (eart.) is observed, accompanied by an increase in the spread.

4.3.7 Unsaturated hydraulic conductivity

The unsaturated hydraulic conductivity K_u, depending on the pressure head, is depicted in Figure 4-7. Wood peat has an outstanding high K_u-value of 500 cm/day at pF 0, whereas sand gyttja with 38 cm/day and amorphous peat (aggr.) with 13 cm/day have the lowest K_u-values. Between pF 1.5 and pF 2 all substrates' K_u-values decrease below 1 cm/day, with a steeper decrease for the substrates with higher K_u-values at pF 0.

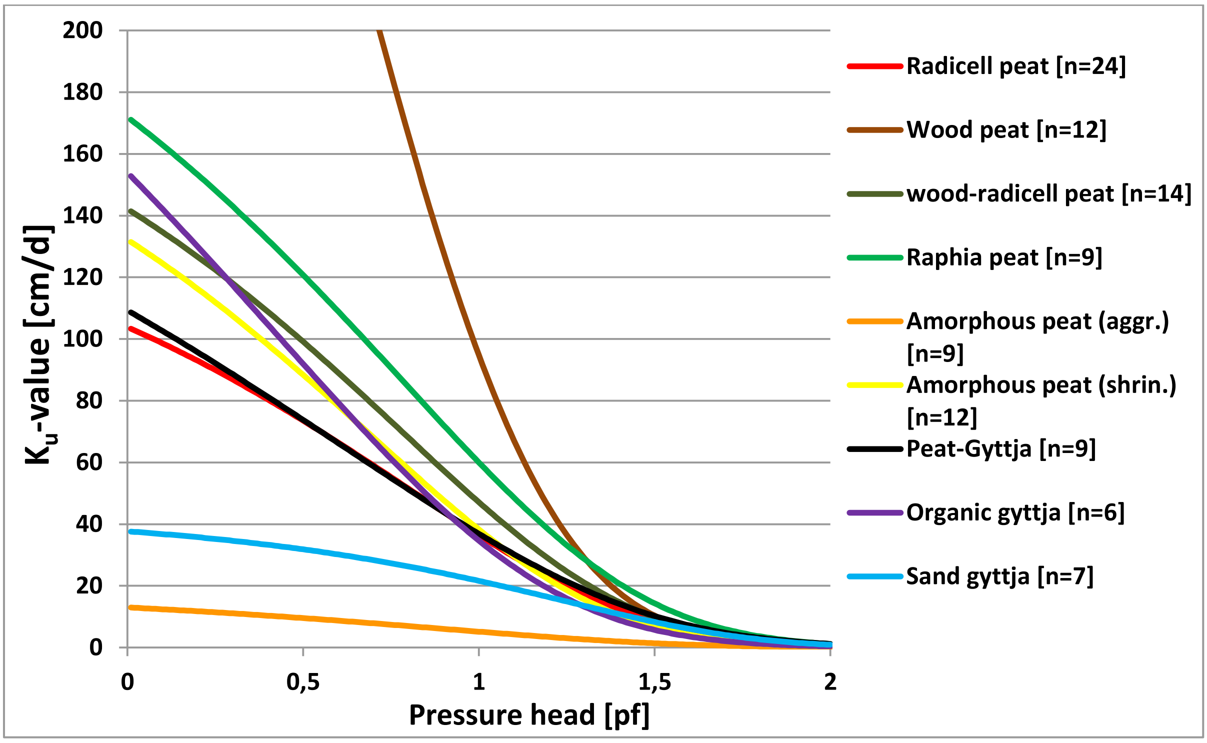


Figure 4-7: Unsaturated hydraulic conductivities calculated with equation 2.

4.3.8 Maximum capillary rise

The maximum capillary rise (Figure 4-8) was calculated for different stationary capillary flows *q,* which represent the evapotranspiration demand (Schwärzel 2000). Grundling et al. (2015) modelled comparable evaporation rates between 2 mm/d in winter and up to 6 mm/day in summer for sedge/reed vegetation in the Mfabeni mire complex. For a better comparison, the results will be described in the following for q = 6 mm/day (at a pressure head of pf 4.2). Greatest capillary rise were determined for peat-gyttja (173 cm) and raphia peat (158 cm). Concerning the common peat substrates, radicell peat (123 cm) and wood-radicell peat (125 cm) show similar patterns, whereas the rise for wood peat (107 cm) is lower. Lower maximum capillary rises were calculated for amorphous peat (shrin.) (97 cm) and amorphous peat (aggr.) (65 cm). Amorphous peat (aggr.) from the site characteristic profile at the second transect of site ID 3 showed the lowest calculated maximum capillary rise (25 cm).

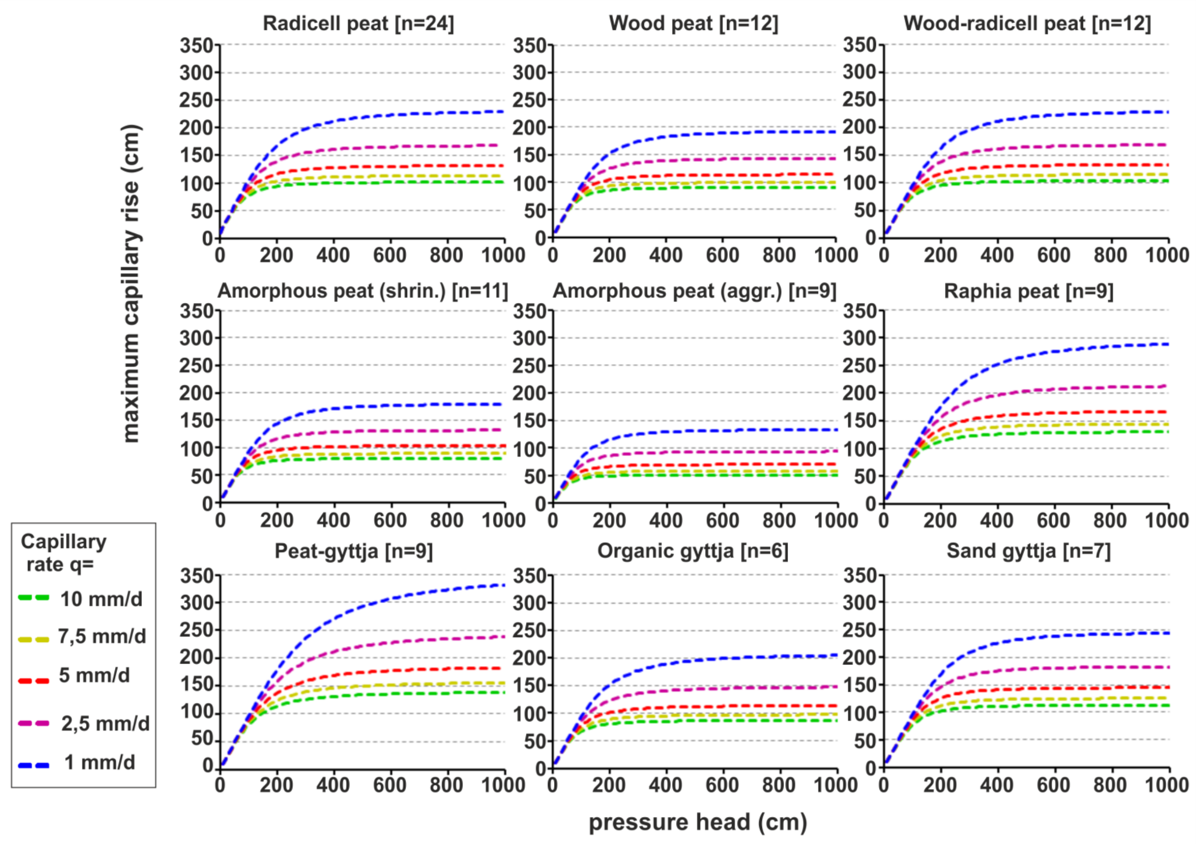


Figure 4-8: Maximum capillary rise given for substrates. Pressure head 100 cm = pF 2; 1000 cm = pF 3.

4.3.9 Potential hydrophobicity

The potential hydrophobicity, as determined by the water drop penetration time test for the different substrates, is given in Figure 4-9. The median of five tests is used in discussing the results. The amplitude of the values, with a logarithmic Y-axis, is most prominent. Except for sand gyttja, the median values for all substrates are strongly or severely hydrophobic, with highest values within the category *extremely hydrophobic*. Of the common peat substrates, radicell peat (2100 seconds) and wood-radicell peat (2700 seconds) show similar characteristics, whereas the median of wood peat lies at 450 seconds. Horizons affected by degradation show a distinctly different pattern. Whereas amorphous peat (shrin.) has a relatively low potential hydrophobicity (186 seconds), it increases with degradation, as evidenced by amorphous (aggr.) (1260 seconds) and amorphous peat (eart.) (1620 seconds**)**.

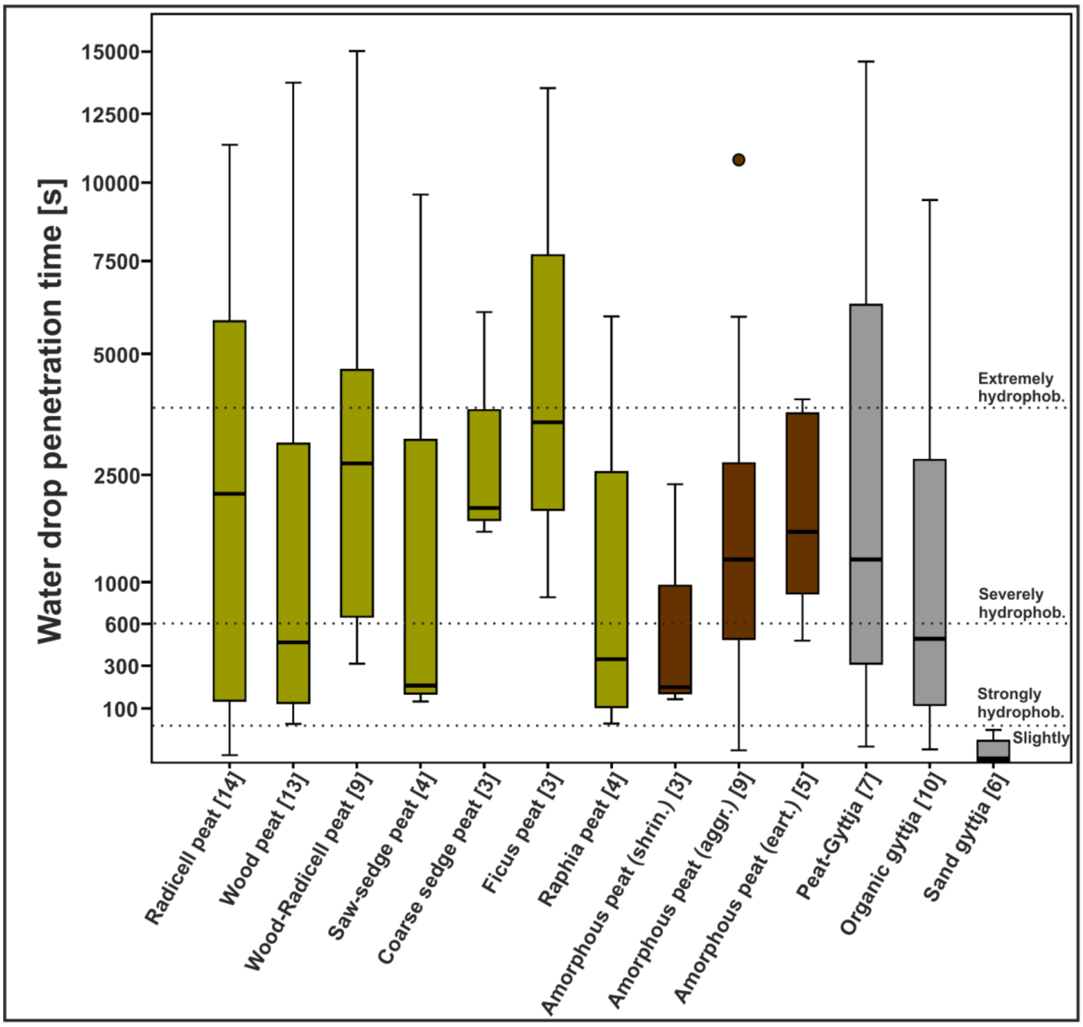


Figure 4-9: Water drop penetration times for the different substrates.

4.4 Discussion

4.4.1 Change of parameters due to degradation

4.4.1.1 BULK DENSITY AND ORGANIC MATTER

The moorsh forming process results from mineralisation and compaction (Zeitz & Velty 2002), which is visible in the higher bulk densities of amorphous peat substrates. A clear increase of the bulk density with degradation intensity was unexpectedly not observed. The attendant development of cracks in amorphous peat substrates might be the reason for that.

Due to the mineralisation of organic matter, its content decreases with continuing degradation. Only raphia peat from the floodplain shows similar low values as a consequence of fluvial mineral inputs from flood events.

4.4.1.2 PORE SIZE DISTRIBUTION AND WATER RETENTION

Total porosity decreases with progressing degradation. Further, there is a distinct decline of macropores and an increase of fine pores. Silins & Rothwell 1998 (in Holden et al. 2004) state that one effect of drainage is the collapse of readily drainable macropores. Zeitz (2001) reports that as a consequence of shrinkage the volume of narrow coarse pores and mesopores is decreasing, which can be supported by the results of this study. Studies conducted on peat substrates in central Europe show the same pattern (Schwärzel 2002; Zeitz & Velty 2002; Schindler et al. 2003, Wallor et al. 2017). As a consequence, the water storage capacity–an important ecosystem function–declines as well.

Organic gyttja and amorphous peat (shrin.) resemble each other in their water retention characteristics, showing that both materials have a similar texture, which also makes them difficult to distinguish during fieldwork. Amorphous peat (shrin.), representing the first state of degradation, exhibits lower water content at low pressure levels than the more common peat substrates, but similar characteristics for pressure levels > pF 1.5.

Of all tested substrates amorphous peat (aggr.) has the lowest water contents at pressure levels < pF 1, except for sand gyttja. Between pressure levels pF 1 and pF 2 amorphous peat (aggr.) reverses its position in this comparison and shows the highest water contents at high pressure levels.

In the first degradation stage (amorphous peat (shrin.)) the water retention characteristics are still similar to those of pristine peat. However, at a modest degradation stage (amorphous peat (aggr.)), the water retention characteristics are severely affected by alterations in the soil structure. A review of other studies shows that amorphous peat (eart.), as representing a major stage of degradation, will yield even lower total pore volumes (Zeitz & Velty 2002, Ilnicki & Zeitz 2003, Schindler et al. 2003). The formation of cracks and aggregates might increase the coarse pore volume, but the continuing decomposition of peat compounds leads to a further increase of fine pores, resulting in a net loss of mesopores (Ilnicki & Zeitz, 2003, Schindler et al. 2003). As mesopores contribute substantially to the available water capacity, peat degradation will also impact vegetation profiles, offering conditions for plants better adapted to these drier environments.

Wood peat with a high content of macropores exhibits the fastest water loss among all examined peatland substrates, as indicated by the relative shape of its water retention curve. Of all investigated peatland substrates, wood peat dries out the fastest and therefore appears to be the most vulnerable.

4.4.1.3 SATURATED HYDRAULIC CONDUCTIVITY

Water movement in the soil takes place in the active pore space. The active pore space includes interconnected pores between different peat particles, but excludes voids and dead-end spaces within the peat particles, such as the remains of plant cells (Quinton et al. 2009). The botanical composition of peat is a major factor of permeability (Rycroft et al. 1975). The high amplitude of K_{sat}-values within certain substrates of this study partly originates from the heterogeneity of the samples in degree of decomposition and bulk density. These two parameters have a major influence on the saturated hydraulic conductivity (Päivänen 1973, Rycroft et al. 1975). Moreover, the uneven distribution of macropores, for example along relict channels of decayed roots, may be responsible for the variations. These preferential flow paths play a crucial role for the water movement in the soil (Liu et al. 2016).

The low K_{sat}-values in saw-sedge peat and coarse sedge peat are likely to be caused by higher percent compositions of organic gyttja, as these substrates are thought to form in shallow open water (Gabriel et al. 2017a). Wood peat, with the highest amount of macropores, has consequently the highest saturated hydraulic conductivity, which is shown by the results of the laboratory method (median = 603 cm/day) and the in-situ auger hole method (median = 1050 cm/day). The high values of the auger hole method probably derives from the fact that parts of the soil containing thicker roots could not be sampled with sample rings, but that these roots have a great importance as preferential flow paths.

Other studies on tropical wood peat observed K_{sat}-value in the same magnitude or higher. Kelly et al (2014) give mean K_{sat} values between 318-1387 cm/day in the topsoil and 142-541 cm/day in the subsoil of peat swamp forests in Peru (Kelly et al. 2014), while topsoil maximum values reached 9500 cm/day. 3000 cm/day were reported for Indonesian peat swamp forests in Kalimantan (Takahashi et al. 1997 in Wösten et al. 2008). Baird et al. (2017), who used piezometers to measure saturated hydraulic conductivity in Panama even reports values up to 47 000 cm/day. Page et al. (2009) state that the mostly fibric and hemic tropical wood peat usually has K_{sat}-values above 1000 cm/day. Wood peat from temperate regions on the other hand is known to have smaller values, between 80-340 cm/day (Gabriel & Roßkopf 2014) or around 24 cm/day (Gnatowski et al. 2010), probably because wood peat occurs in those latitudes mainly in higher degrees of decomposition (Gnatowski et al. 2010). The high K_{sat}-values of more than 1000 cm/day occur in wide coarse pores related to tree roots. The results reveal the existence of such root pores in at least every few square decimetres, within a vertical cross section of a peat swamp forest. Hence, their contribution to water flow within a peatland of wood peat would be of crucial and much greater importance than the bulk of the remaining pores. This, however, would only be the case, if the root pores form a connected flow network. Our results do not allow such a conclusion. Other methods, focussing on the peatland as a whole, like tracer experiments or non-penetrative methods must be applied to investigate this issue. This leaves the hypothesis that swamp forest peatlands are more sensitive to aeration after the installation of drainage ditches, as water drains more rapidly in them than in other peat types. In addition, the parts between root pores might be more difficult to wet, because infiltrating rainwater or rising ground water will move principally in the root pores.

Further, the conditions of laminar water flow are not given anymore more with K_{sat}-values exceeding 1000 cm/day. Strictly speaking, the formula for the calculation of the K_{sat}-values cannot be applied anymore. Nevertheless, we measured those high permeabilities and calculated them into K_{sat}-values in order to make them comparable.

The mentioned collapse and contraction of pores as a consequence of mineralisation reduces the saturated hydraulic conductivity in amorphous peat (shrin.) to 11 cm/day. With proceeding degradation, the volume of primary pores between fibres is decreasing; at the same time, the volume of secondary pore spaces due to proceeding aggregation and creation of cracks is increasing. Therefore, K_{sat}-values are increasing from amorphous peat (shrin.) to amorphous peat (aggr.) with around 100 cm/day and again to amorphous peat (eart.). with around 500 cm/day. Similar values with 500 cm/day for degraded peat horizons with shrinkage cracks in the soil matrix were reported by Scholz (1985) (in Zeitz 2001, p.90).

Zeitz (2001) states that low K_{sat}-values may complicate rewetting measures of drained peatlands, as the distribution of water from blocked drainage ditches into the peat body is impeded. Hence, this kind of problem might also be encountered in South African peat shrinkage horizons as well.

4.4.1.4 UNSATURATED HYDRAULIC CONDUCTIVITY AND CAPILLARY RISE

The unsaturated hydraulic conductivity is positively related to the soil moisture content, as the flow network of connected pores becomes diminished, when the water content is decreasing (Schwärzel et al. 2006, Quinton et al 2009). The results of this study indicate that the initial stage of degradation does not have severe consequences for K_u, as the curves of amorphous peat (shrin.) show a similar shape as most of the pristine peat substrates. Between amorphous peat (shrin.) and amorphous peat (aggr.), however, a distinct decline is observed, due to the decreased volume of narrow coarse pores and mesopores. The reduced unsaturated conductivity in amorphous peat (aggr.) bears implications for restoration, as Zeitz (2001) identifies it as one of the problems for water distribution into the area around closed drainage ditches. Ilnicki & Zeitz (2003) and Zeitz (2003) show figures with a gradual decline of K_u with degradation, over earthification horizons to grainy moorsh horizons. Schwärzel et al. (2002), however, state that K_u-values at low pressure levels up to pF 2, are higher in very degraded grainy moorsh horizons, due to a higher volume of macropores. The high values of wood peat for pressure levels below pF 1.5 are a consequence of its high volume of coarse pores.

Closely related to the unsaturated hydraulic conductivity is the capillary rise (Brandyk et al. 1986). The values for the maximum rise in this study are somewhat higher than values yielded by other studies, e.g. 70-160 cm in Ilnicki & Zeitz (2003), which might be a hint for an overestimation of K_{sat}-values in this study. Zeitz (2001) and Ilnicki & Zeitz (2003) have reported maximum heights of <10 cm for earthified and grainy moorsh horizons. Unfortunately, in this study no examinations could be realised for earthified horizons. The sample from site ID3 with a maximum capillary rise of 25 cm, which is only a representative for the second severest degradation type in this study, show that the literature values for severely degraded topsoils of less than <10 cm seem realistic for the South African peatlands as well. This change of water availability in topsoil horizons also entails a vegetation change. In colder climates, peat accumulating vegetation like sphagnum mosses, might be replaced by vegetation, which does not accumulate peat (Eggelsmann et al. 1993). It is unknown if this is also the case for South African reed-sedge mires and peat swamp forests, but should be considered, for example in the case of interdune depressions affected by afforestation.

Because the top 20-30 cm of peatlands typically show several different horizons, especially if degraded, it is difficult to interpret unsaturated hydraulic conductivity and capillary rise directly. The results rather serve as tendencies, and therefore have a value for a comparative evaluation. Among the three common peat types, wood peat has the lowest maximum capillary rise. Consequently, the HGMTs channelled valley-bottom and unchannelled valley-bottom with a high occurrence of wood peat, are at a greater risk of drying out than the interdune depressions, where peat gyttja and radicell peat display higher capillary rises at same pressure head levels.

4.4.1.5 HYDROPHOBICITY

Hydrophobicity, or water repellency, in organic soils is closely negatively related to soil moisture and occurs when the soil moisture content falls below a critical value (Dekker & Ritsema 2000, Brandyk et al. 2003, Winarna et al. 2016). Winarna et al. (2016) derived values for two tropical peatlands from Indonesia, which turned hydrophobic when the water content (water in relation to peat weight) fell below 260%, and 160% respectively. The water repellency determined with the water drop penetration time test on air-dry samples therefore reflects the potential hydrophobicity (Dekker & Ritsema 1999). The potential hydrophobicity decreases with decomposition, because hydrophobic tissues, such as lipids and waxes, within the peat become decomposed as well (Doerr et al. 2000). The amorphous peat substrates, which are still “strongly to severely” hydrophobic, are relatively less water repellent than most pristine substrates. As a consequence, water repellency is especially strong in recently drained peatlands and will thus contribute to maintain aeration and therefore fast decomposition, as it hampers rewetting due to rain or capillary rise (Doerr et al. 2000). In the course of ongoing decomposition, the hydrophobicity then gradually increases again. The assumption that hydrophobicity increases with degradation to values above the ones for dry pristine peat, as stated by Stegmann & Zeitz 2001, could not be confirmed. Though, at least this factor does not seem to play a limiting factor for restoration efforts.

4.4.2 Degradation stages and recovery prospects

The study sites showed different intensities of degradation, from shallow peat shrinkage horizons to up to 30 cm of dry earthification horizons.

The occurrence of amorphous peat without cracks and soil structure was a typical feature in the topsoil horizons of sites UCVB (1) and UCVB (2). These sites are in succession after cultivation, indicating that the degradation during the time of drainage did not reach a point where the formation of soil structure was irreversible. However, the exact period of cultivation and drainage of those sites is not known to the authors, so further interpretations cannot be made. A new radicell peat layer by the reed-sedge succession vegetation is currently forming within the topsoil horizons of amorphous peat. The greatest hydrological alteration in amorphous peat (shrin.) is the decrease of saturated hydraulic conductivity. A full recovery of hydrological properties will also depend on the new input of radicells by the succession vegetation, for establishing the macropore system.

The second degradation stage, indicated by amorphous peat (aggr.), already implicates alteration of the soil structure and hence hydrological properties which are expected to be irreversible

(Schumann and Joosten 2008). With the reduced total pore space, the water storage capacity sinks. This further decreases the capacity of capillary rise, which might be detrimental to plants in times of drought. In amorphous peat (eart.), these characteristics intensify. Further, the high K_{sat}-values are likely to hamper rewetting efforts, as they present preferential flow paths capable to continuously discharge water.

Amorphous peat (moor.), as the most severe type of degradation, was not encountered in the transects of the degraded sites, indicating that drainage did not occur for a time sufficiently long to reach this state. However, it is known from other sites in South Africa, for example the Vazi peatland, which dried profoundly as a consequence of *Pinus* plantations and was later several times afflicted by peat fires (Grundling & Blackmore 1998). Once such a stage is reached, natural recovery is not possible, as the vegetation cannot recolonise the harsh, bare burned areas because of the high salt content, high temperatures and evaporation rates.

4.4.3 Subsidence and peat surface oscillation

Subsidence is a product of consolidation (loss of buoyancy), shrinkage and peat oxidation. The rate of subsidence depends on temperature and is higher in warmer climates (Wösten et al. 1997). In a comparable study, Wösten et al. (1997) indicate an average subsidence of about 3 cm per year, for Malayan peat swamp forest at an average water table depth of 50 cm. Next to water table depth and temperature, the third driver for peat subsidence is time. The first years of drainage are usually marked by a high rate of subsidence due to consolidation and is declining in the following years to a rather constant value. With consolidation the aeration decreases, resulting in a decreasing rate of mineralisation (Wösten 1997, Renger et al 2002, Zeitz 2003, Hooijer et al. 2012). This decline can also be seen in the contents of organic matter with a mean of 79% for pristine peat, 69% for amorphous peat (shrin.), 64 % for amorphous peat (aggr.) and 62% for amorphous peat (eart.).

Pristine substrates will therefore subside considerably when drained for the first time. The progressing subsidence will slow down with the degradation intensity. A higher subsidence rate of wood peat is expected, as the coarse pores enhance aeration and reduce capillary rise.

Degraded peatlands, with compacted and compressed surface horizons have a reduced buoyancy and therefore reduced peat surface oscillations (Stegmann & Zeitz 2001, Whittington & Price 2006). The dominating factor for surface oscillations in pristine peatlands is the peat-forming vegetation (Stegmann et al. 2001). Grundling et al. (2012) measured in the South African Mfabeni mire complex water table fluctuations of 40 cm during a period of two years. At the same time they recorded peat surface oscillation of about 10 cm in the sedge-reed dominated parts, whereas in the parts with peat swamp forest, no significant oscillations were noted. They conclude that the weight of peat swamp forest vegetation, the deep anchorage of the roots and the absence of aerenchym tissues reduce to almost zero. The only peatlands in Maputaland with the capacity to mitigate mineralisation during droughts are consequently those with reed-sedge vegetation.

4.4.4 Consequences of degradation and threats to HGMTs

The properties of the main peatland substrates and substrates from the degradation horizons are compared to each other in Table 4-5, relative to the highest and lowest observations of this study. The estimated effects of hydrological changes for the different HGMTs are given in Table 4-6.

Table 4-5: Comparison of substrate properties relative to the highest and lowest observations of this study: TPV = Total pore volume; AWC = Plant available water content; OOO = high; OO = medium; O = low; <O = very low; *= based on literature.

Substrate	TPV	AWC	K_{sat}	Capillary action	Hydrophobicity
Amorph (shrin.)	OO	OO	O	OO	OO
Amorph (aggr.)	O	O	OO	O	OOO
Amorph (eart.)	O*	O*	OOO	<O*	OOO
Radicell	OOO	OOO	OO	OOO	OOO
Wood	OOO	O	OOO	OO	OO
Wood-radicell	OOO	OOO	OOO	OOO	OOO
Peat-gyttja	OOO	OOO	OO	OOO	OOO
Organic gyttja	OO	OO	O	OO	OO

Table 4-6: Overview of site types and their expected reaction to hydrological changes.

HGMT	Vegetation type/ main substrate	Main water Source	Reaction to hydrological changes		
			Drainage ditch	**Ditch blocking**	**Water abstraction (plantations) and drought**
UCVB	Peat swamp forest/ Wood peat	Groundwater flow-through (Groundwater table = peatland water table)	-Drainage works very effectively, good aeration through coarse pores, low capillary action, results in swift decomposition. -Loss of carbon and water storage, compaction, subsidence.	-In low and medium degradation stages positive response and regain of hydrological functions. -Recovery of typical vegetation a matter of decades. -In severe degradation state drainage can continue along desiccation cracks.	-Very vulnerable peatland type. -All parts of the peatland affectted, as peatland surface is usually flat. -Less capillary action than peatlands with other peat types. -Because of fixed acrotelm no peatland surface oscillation. Mineralisation is greater than in ID and UCVB with reed-sedge communities. -Risk of fire during drought is low because fire usually does not enter an intact peat swamp forest, except in cleared and/or drained part along ditches.
	Reed - sedge community/ Radicell peat	Groundwater flow-through (Groundwater table = peatland water table)	-Drainage works effectively, high capillary action, decomposetion -Loss of carbon storage and water storage, compaction subsidence.	-In low and medium degradation stages positive response and regain of hydrological functions -Recovery of typical vegetation within years. -In severe degradation state drainage can continue along desiccation cracks.	-Vulnerable peatland type. -All parts of the peatland affected, as peatland surface is usually flat. -Pristine peatlands, with limited ability of peatland surface oscillation, may mitigate mineralisation. -High risk of fire. If fire peatland is already degraded, fire spreads through desiccation cracks.
CVB	Peat swamp forest/ Wood peat	Groundwater discharge (Peatland water table lower than groundwater table)	-Drainage works very effectively, good aeration through coarse pores, low capillary action, results in swift decomposition. -Loss of carbon storage, water storage, compaction, subsidence.	-In low and medium degradation stages positive response and regain of hydrological functions. -Recovery of typical vegetation a matter of decades. -In severe degradation state drainage can continue along desiccation cracks.	-Less vulnerable peatland type. -Effects of groundwater drawdown in the valley catchment likely to be less compared to UCVB and ID, as the groundwater table doesn't directly correspond with the peatlands water table. -Plantations outside the topographically defined catchment in the recharge area of the aquifer contribute to drier conditions. Drying of peat in the highest parts of the peatland's relief is expected first, or in drained lower parts along ditches. -Risk of fire during drought is low because fire usually does not enter an intact peat swamp forest, except in cleared and drained part along ditches

HGMT	Vegetation type/main substrate	Main water Source	Reaction to hydrological changes		
			Drainage ditch	Ditch blocking	Water abstraction (plantations) and drought
CVB	Peat swamp forest/ Wood peat	Groundwater discharge (Peatland water table lower than groundwater table)	-Drainage works very effectively, good aeration through coarse pores, low capillary action, results in swift decomposition. -Loss of carbon storage, water storage, compaction, subsidence.	-In low and medium degradation stages positive response and regain of hydrological functions. -Recovery of typical vegetation a matter of decades. -In severe degradation state drainage can continue along desiccation cracks.	-Less vulnerable peatland type. -Effects of groundwater draw-down in the valley catchment likely to be less compared to UCVB and ID, as the groundwater table doesn't directly correspond with the peatlands water table. -Plantations outside the topographically defined catchment in the recharge area of the aquifer contribute to drier conditions. Drying of peat in the highest parts of the peatland's relief is expected first, or in drained lower parts along ditches. -Risk of fire during drought is low because fire usually does not enter an intact peat swamp forest, except in cleared and drained part along ditches
ID	Reed sedge community / Radicell peat, peat gyttja	Groundwater flow-through (Groundwater table = peatland water table)	-Drainage of inter-dune depressions is not possible because of the closed shape. Cultivation is usually practised on raised beds. -Mineralisation of organic matter takes place in the raised beds.	Not applicable	-Vulnerable peatland type. -All parts of the peatland affected, as peatland surface is usually flat. -Pristine peatlands, with a topsoil layer of radicell peat and a fully developed reed-sedge vegetation, have a limited ability of peatland surface oscillation and may mitigate mineralisation. -Sites with mayor layers of organic gyttja more endangered of drying (lower capillary rise). -Cultivated, turbated sites with organic gyttja as topsoil probably the most endangered of drying and mineralisation. -High risk of fire. If fire peatland is already degraded, fire spreads through desiccation cracks.

4.5 Conclusions

As Maputaland's peatlands do not depend on rain water but on surplus of ground water due to their beneficial hydrogeomorphic setting, they are hydrologically dependent on their surroundings and therefore management of water sources is essential. Hence, afforestation in the recharge area of interdune depressions, seeps and valley-bottoms cause degradation of peatlands in these HGMTs. Peatlands that contain wood peat occur in channelled and unchannelled valley-bottoms and are the ones where after drainage the fastest degradation is expected. Therefore, conservation priorities should be given to these peatland types. Cultivation of peatlands in valley-bottoms should abandon drainage and be preferably located along the fringes where the natural water table has the desired depth. In interdune depressions the cultivation along the fringes is also more sound for the peatland, as organic material of raised beds are exposed to aerobic conditions as well.

Concerning water and carbon storage functions, conservation priorities should be given to pristine peatlands rather than to already degraded ones, as drainage would lead there to the highest losses. For restoration purposes the causes of degradation need to be reversed first. The following interventions can be considered: Block drains, even on a seasonal basis to allow subsistence agriculture to rewet the peat. Protect exposed peat areas by mulching to conserve moisture. Deactivate any erosion points and do not burn waste/dry vegetation on degraded peat. Plantations close to interdune depression peatlands should be removed. Rewetting measures must be monitored properly. If drainage ditches are blocked downslope and some parts of the peatland's topsoil still remain dry, it has to be supposed that water continuously drains through desiccation cracks. In that case, a barrier out of substrate with a low hydraulic conductivity (e.g. amorphous peat (shrin.)) can been implemented in the crack containing topsoil of the degraded peatland, perpendicular to the flow direction and from one side to the other. These interventions should not be commenced without a wise use programme aimed at educating local communities, building capacity and changing land use behaviour.

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5 Maputaland’s Peatlands and Climate Change

5.1 Introduction

Anthropogenic climate change is a global problem, brought about by the emission of so called greenhouse gases. The greatest contribution comes from carbon dioxide (CO_2) (IPCC 2014). The CO_2 gas has manifold sources, which are directly or indirectly related to human activities. One of those sources is the emission by mineralising peat from disturbed peatlands all around the world (Strack 2008). The emission of greenhouse gases by mineralisation of peatlands in Maputaland is rather insignificant, given a total size of about 20.250 hectares (Grundling & Grobler 2005), in comparison to circa 400.000.000 hectares of peatlands worldwide (Strack 2008). On the other hand, climate and sea-level are important factors for peat accumulation in Maputaland’s peatlands (Grundling et al. 2013, Gabriel 2017), such that they appear rather vulnerable to climate change. Vulnerability, in the context of peatlands, means the possible mineralisation of organic matter when facing deficits in the water regime (Fell et al. 2016). Specifically, the effects of climate change on seasonality might disturb the balance between carbon accumulation and decomposition (Yu et al., 2011). Mineralisation of organic matter will be accompanied by losses of the ecological functions and ecosystem services of a peatland (Schuhmann & Joosten 2008). Local communities with a great number of people practicing subsistence farming rely heavily on the ecosystem services of peatlands and specifically on the provision of water, fertile farm land, and (ground)water flow regulation (Grundling A. et al. 2016).

What consequences can be expected for peatlands in respect of the current climate change scenarios for Maputaland? Which hydrogeomorphic wetland types are most vulnerable?

5.2 Climate Change scenarios

In their fifth assessment report, the Intergovernmental Panel on Climate Change (IPCC) introduced a new concept of climate changes scenarios - the so called “Representative Concentration Pathways” - or RCPs (IPCC 2014). These scenarios include various political options to reduce the greenhouse gas emissions and are named after the increase of the Earth’s Energy Budget (in W/m^2) by the year 2100, in comparison with the preindustrial level in 1850. “RCP4.5”, for example, corresponds to a scenario in which the budget is 4.5 W/m^2 higher in the year 2100 than it was in 1850 (IPCC 2014). The following discussion will be based on the South African “Climate Change Reference Atlas 2017”, presenting projections for two climate change scenarios, which were calculated with nine different scientifically recognised models (SAWS 2017). The first scenario, RCP4.5, is an optimistic one involving the reduction of greenhouse gas emissions and a ceiling, in the year 2100, of about 650 ppm CO_2-equivalent concentrations (IPCC 2014). The second, RCP8.5, is known as “the business as usual scenario”. In this case political decision making will continue to be dominated by capitalist interest rather than by rational decisions, and by the year 2100 the CO_2-equivalent concentration will be about 1370 ppm (IPCC 2014).

5.3 Predicted Climate Change until 2100 in Maputaland

5.3.1 Temperature

The following data (Table 5-1) are all obtained from the Climate Change Reference Atlas 2017 (SAWS 2017) for the area of the Maputaland Coastal Plain.

Table 5-1: Change of temperature (projection medians) in Maputaland with reference to 1976-2005 as base period.

Climate Change Scenario	Period	Temperature change
RCP 4.5 "The optimistic scenario"	2036-2065	+ 1.5-2°C
	2066-2095	+ 1.5-2°C
RCP 8.5 "The business as usual scenario"	2036-2065	+ 1.5-2°C
	2066-2095	+ 3-4°C

Both climate change scenarios indicate a slight reduction in seasonal fluctuations, due to a relative temperature increase of about 0.5°C between the cooler months, from June to November, and the hotter summer months, from December to May.

5.3.2 Precipitation

The following data (Table 5-2) are all obtained from the Climate Change Reference Atlas 2017 (SAWS 2017) for the area of the Maputaland Coastal Plain.

Table 5-2: Change of precipitation (projection medians) in Maputaland with reference to 1976-2005 as base period.

Climate Change Scenario	Period	Precipitation change
RCP 4.5 ”The optimistic scenario”	2036-2065	- 0-5%
	2066-2095	- 0-5%
RCP 8.5 "The business as usual scenario"	2036-2065	- 0-5%
	2066-2095	- 5-10%

The projections of the two climate change scenarios for the area of the Maputaland Coastal Plain display some differences regarding the development of seasonal precipitation fluctuations. The RCP4.5 model indicates for the period 2065-2095, slightly higher precipitations from December to February (+ ca. 0-5 mm) and from March to May (+ ca. 5-10 mm). From June to August (- ca. 0-5 mm) and from September to November (- ca. 10-20 mm) precipitation levels could be expected to be slightly lower than they are at present. This implies a slight increase in seasonal variation, and slightly drier conditions overall. The RCP8.5 scenario indicates, for the period 2066-2095, slightly drier conditions from December to March and from June to August (- ca. 0-5 mm), followed by a considerable falling off in precipitation levels between September and November (- ca. 30-50 mm). Thus, in the RCP8.5 scenario seasonal variation is expected to be more pronounced, while, overall, conditions are significantly drier.

5.3.3 Sea-level

According to the IPCC (2014), the sea-level rose 0.19 m between 1901 and 2010. Scenario RCP4.5 predicts a further rise of 0.26 m for the period 2046-2065 and 0.47 m for the period 2081-2100. RCP8.5 predicts a further rise of 0.3 m for the period 2046-2065 and 0.63 m for the period 2081-2100 (IPCC 2014). Recent publications indicate that the IPCC (2014) has underestimated the effect of a possible disintegration of large fractions of the Antarctic ice shield (Le Bars et al. 2017; Wong et al. 2017). Wong et al. (2017 and Le Bars et al. (2017) predict sea-level rises, for the RCP8.5 scenario, of 150 cm and 184 cm respectively.

5.3.4 Consequences on the hydrological regime

Two important consequences of climate change will influence the hydrological conditions of the Maputaland Coastal Plain. The first is the projected change of the precipitation and evapotranspiration pattern, and the second is the predicted sea-level rise. These shifts will have opposite effects on the groundwater table (Figure 5-1). The effect of the sea-level rise, however, will diminish with increasing vertical and horizontal distance to the ocean.

The climate scenario projections show a small reduction in precipitation and an increase of temperature. Abtew & Melesse (2013) state: “Evapotranspiration increases with increasing temperature, increasing radiation, decreasing humidity, and increasing wind speed. Decreasing rainfall contributes to increasing evapotranspiration through increase in clear skies, increase in temperature, and lower humidity.” (Abtew & Melaesse (2013) in: Evaporation and Evapotranspiration – Measurements and Estimations; page 197).

This will have a negative effect on the shallow Maputaland aquifer, which is the main water source and the lifeline of the peatlands in Maputaland (Grundling A. 2014). The aquifer is recharged by the precipitation received by the area between the Indian Ocean Coast and the Lebombo Mountains, and so the decrease in rainfall, coupled with the increase in evapotranspiration in this zone will reduce the aquifer’s volume of water.

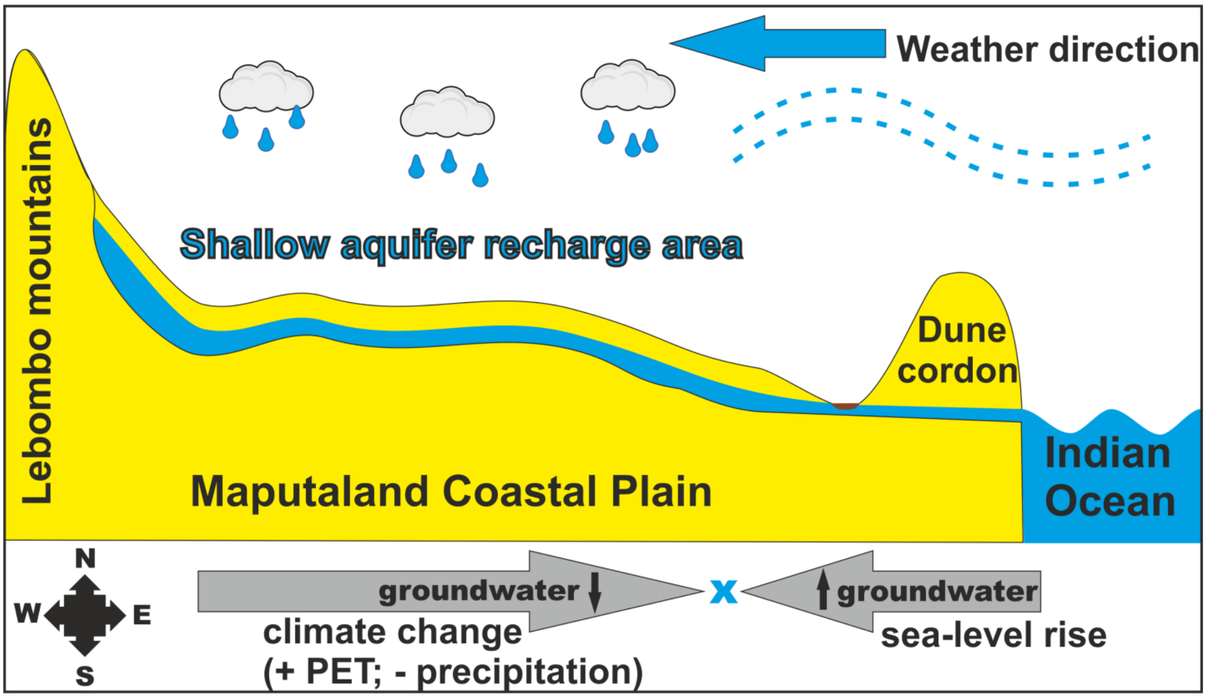

Figure 5-1: Schematic view of the Maputaland Coastal Plain (proportions exaggerated): shallow aquifer in blue and the expected effects of climate change on groundwater as grey arrows. Blue cross marks the zone where the effects outweigh each other.

According to the conclusions drawn in Chapter 2, the projected sea-level rise will also lead to a rise of the water table, inland. However, the sea-level rise will probably affect only the peatlands on the lowland part of the Maputaland Coastal Plain - for example around Kosi Bay, Lake Sibaya and Lake St. Lucia. As we have seen, peatlands in proximity to the ocean, such as the investigated Matitimani valley, are prone to increased peat accumulation, particularly when they contain peat swamp forest (wood peat exhibited the highest accumulation rates of all peat types). In contrast, due to their vertical distance from the sea-level, peatlands on the upper part of the Maputaland Coastal Plain, such as the Muzi Swamp, are not prone to benefit from a sea-level rise. The great uncertainty in the projections of the sea-level rise make it very to estimate precisely the degree to which the hydrological balance of the peatlands might be positively affected.

Peatlands farther away from the ocean, where the positive effect of sea-level rise peters out, will face stress by the reduction of the water volume in the shallow Maputaland aquifer. The expected effects on peatlands in different hydrogeomorphic wetland types are shown in Figure 5-2. Peatlands in interdune depressions and unchannelled valley-bottoms will probably be the ones most affected, as their water table corresponds directly to the groundwater table. As these water tables are naturally subject to strong seasonal and extra seasonal fluctuations (Grundling A. 2014, Gabriel et al. 2017), the impact of climate change and the resulting water deficit are difficult to estimate, but longer periods of topsoil dryness must be expected, and these could eventually lead to mineralisation.

Unchannelled valley-bottoms with peat swamp forest might be the worst affected, as they do not have the capability of peat surface oscillation to mitigate water table draw-downs. Furthermore, they have a lower capillary rise as peat substrates originating from non-forest vegetation. Water discharge into seeps might also fall dry, exposing peatland surfaces to aerobic conditions and mineralisation. Peatlands in channelled valley-bottoms, with the characteristic that peatland water tables are lower than the surrounding groundwater table, seem less endangered than peatlands in other hydrogeomorphic settings. However, with a reduction in the water-table, a movement of the discharge zone might occur, shifting the point where the groundwater enters towards the central part of the peatland and allowing desiccation of the fringes.

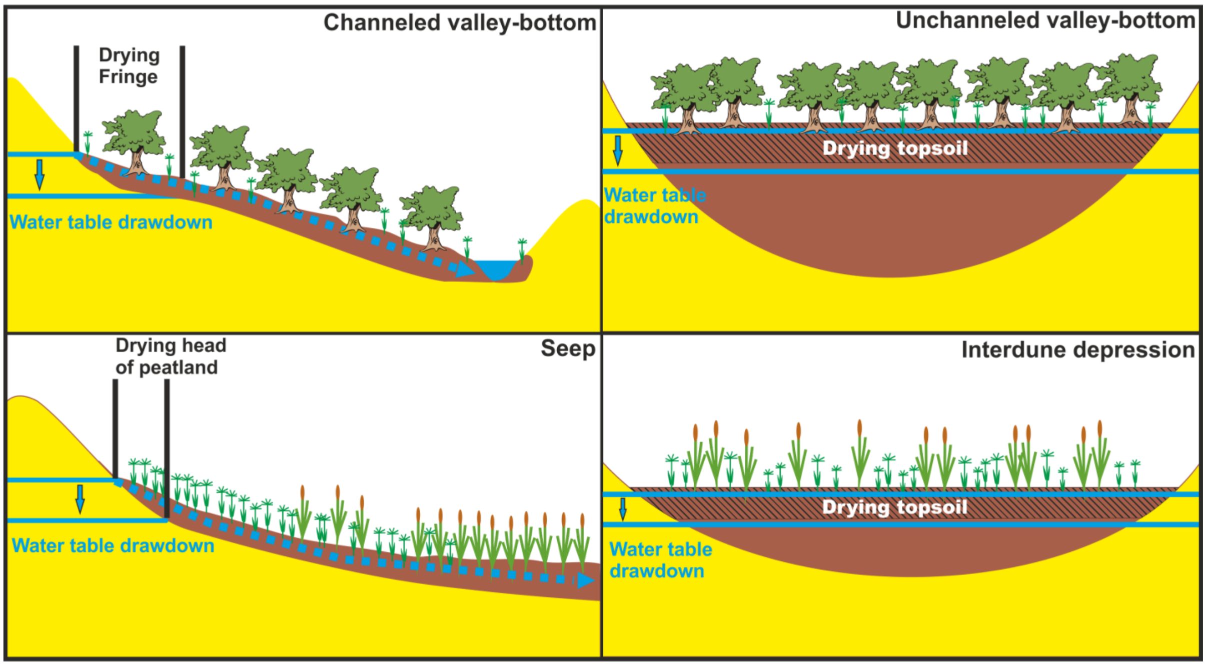

Figure 5-2: Likely effects of water deficit on peatlands in different hydrogeomorphic wetland types

5.4 Summary

What consequences for peatlands can be expected in regard to the current climate change scenarios for Maputaland?

Peatlands in proximity to the coast will benefit from rising sea-levels. Inland, the effect peters out and peatlands will face higher water stress due to diminished recharge of the shallow Maputaland aquifer.

Which hydrogeomorphic wetland types are most vulnerable?

Beyond the point where the benefit from sea-level rise peters out, peatlands in unchannelled valley-bottoms with peat swamp forest are the most vulnerable to topsoil mineralisation. They are followed by peatlands in interdune depressions and unchannelled valley-bottoms with reed-sedge vegetation. Peatlands in seeps and channelled valley-bottoms are vulnerable to mineralisation at the fringes when reduced water volume in the aquifer lowers the groundwater discharge zone.

5.5 Research requirements

Based on the projections of the "business as usual" scenario, a severe increase in potential evapotranspiration can be anticipated. However, neither further specification of changes on the water balance can be made, nor a definition of threshold values. This contemplation based on the climate change scenario projections from the reference Atlas for Climate Change 2017(SAWS 2017) can only serve to point out tendencies. Solid hydrological modelling, including the consideration of the changes in evapotranspiration, is necessary for more detailed predictions on the effects of climate change on the hydrological conditions of the Maputaland Coastal Plain. However, the tendencies leave no doubt as to the fact that climate change will put additional stress on Maputalands peatlands.

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6 Synthesis

6.1 Peatlands in Maputaland

The history of peatlands in Maputaland (Figure 6-1) is related to the post glacial sea-level rise and the beginning of the Holocene temperature optimum which brought increasing moisture in the South African summer rain region (Scott & Lee-Thorp 2004, Chapter 2). In the later Holocene, positive feedback effects on the water tables in upper catchments were generated by the formation of peatlands in catchment drainage lines, which reduced the water outflow. The higher water tables in the upper catchment areas eventually led to further peatland initiations and peat accumulation (Grundling A. 2014, Chapter 2). When human land use started, the surface and volume of peatlands started to decline. First shifting cultivation practices (slash and burn), and then permanent cultivation with drainage systems, forestry and water abstraction related to the use of land by a fast growing rural population negatively affected the peatlands (Bruton et al. 1980, Sliva et al. 2004). To the present day, an unknown but considerable amount of peatland volume has been lost in this way.

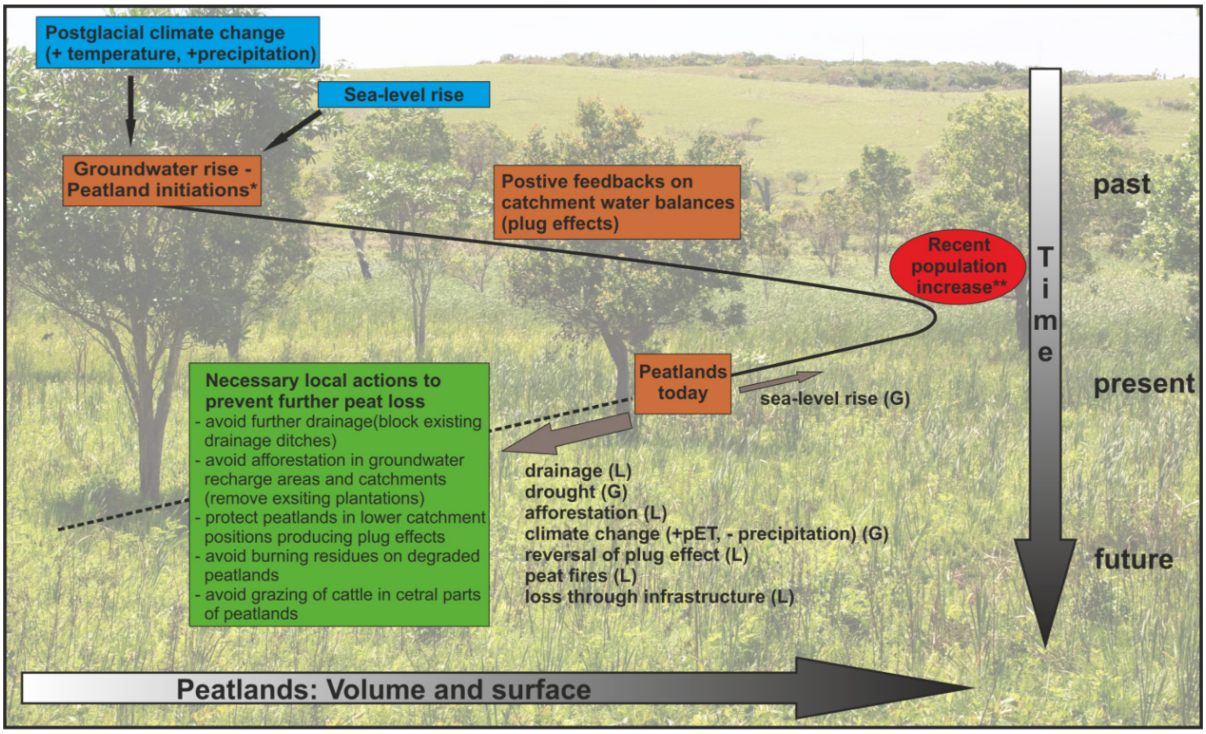

Figure 6-1: Schematic development of peatlands at the Maputaland Coastal Plain since the early Holocene. (G) refers to effects produced by anthropogenic actions on a global scale; (L) refers to effects produced by anthropogenic actions on a local scale.

* Two exceptions for Pleistocene peatland initiations exist. Mfabeni peatland (45.000 BP) and Mhlanga (33.000 BP) (Grundling et al. 2000).

** Although humans have inhabited the Maputaland Coastal Plaine for thousands of years (Bruton et al., 1980), the massive impact of human activities on peatlands has only commenced during the last few decades (Sliva et al. 2004).

In the future, peatlands will be continuously threatened by various anthropogenic causes on local, both on a local, and on a global scale. As indicated in Figure 6-1, certain actions on a local level are necessary in order to avoid further loss of peatlands and their valuable functions. Firstly, conservation priorities and measures need to be defined to protect the remaining peatlands. Secondly, existing land use needs to be transformed, with a set of sustainable practices which do not lead to further peat mineralisation. Finally, restoration of already degraded peatlands should be considered, in an effort to regenerate them and enable them to fulfil their previous ecological functions.

6.2 Conservation

In order to prevent the further degradation of peatlands, conservation measures are necessary. The socio-political aspects of conservation will be omitted in this dissertation, as environmental laws, land use planning and the execution of conservation measures in South African are especially complex. The heterogeneous web of (opposing) actors, with a fast growing rural population, national institutions, tribal authorities and different land ownerships (such as private individuals, tribal communities, and private corporations), needs to be addressed properly and carefully in a separate study. Hence, this dissertation will merely discuss the prospects for conservation in a natural, landscape ecological context.

The first and most important restoration measure is the avoidance of further peatland drainage. As drainage is a general part of local cultivation practice, measures to protect peatland soils will be presented in the next subchapter, together with the discussion of more sustainable cultivation methods.

One big threat to peatlands is decreasing water tables associated with forestry plantations. Water abstraction by the trees depletes the volume of water in the shallow Maputaland aquifer (Von Roeder 2014). The establishment of new plantations in the recharge area must therefore be avoided. Moreover, severe draw-down of the water table under, and in direct vicinity of plantations occurs. Brites & Vermeulen (2013) measured a water table drop of 10-16 m under a *Eucalyptus* plantation close to Lake St. Lucia over a period of 13 years. To prevent harm to peatlands and wetlands, buffer zones need to be established around them. Von Roeder (2014) showed, in a sample calculation, a radius of influence of 120-360 m around *Eucalyptus* plantations, but he considers that it is impossible to make generalisations about the individual buffer requirements. These depend on the hydrogeomorphic setting, the size of a planned plantation, and the rooting depth and evapotranspiration rate of the tree species involved.

The loss of peatlands through infrastructure should be avoided. If roads need to be constructed through peatland areas, efforts should be made to ensure that the hydrological functioning of the peatland is maintained at all cost.

Cattle grazing can damage peatlands as well. It changes the ecological conditions through eutrification by the cattle’s faeces and it leads to soil compaction (Chapter 4). Therefore, cattle grazing should be avoided in the central parts of peatlands.

It is also important to define conservation priorities, since they are a valuable tool for the elaboration of conservation plans. On every occasion when different conservation and restoration options are balanced against each other, conservation priorities can facilitate the decision making. For example, when local institutions begin negotiations concerning the removal of forestry plantations there is a need for them to identify target areas around peatlands in different hydrogeomorphic settings. Therefore, four main conservation parameters will be evaluated, according to the HGMTs.

The first parameter is the substrate qualities. The priority in this case is defined by the vulnerability of a HGMT with respect to its typical substrates. Chapter 4 describes the high susceptibility of wood peat to subsidence, and its low capillary rise. Therefore, channelled valley-bottoms and unchannelled valley-bottoms get the highest priority in respect of this parameter. The substrates of interdune depressions and seeps are also susceptible to subsidence, and so they should be evaluated as medium priority.

The regeneration time of the natural vegetation after removal (for example for cultivation), is a further conservation parameter. Typical reed-sedge vegetation, which occurs in interdune depressions and seeps, recolonises an abandoned and formerly cultivated peatland soil within one or two years. The reason for this is abundant seedbank in preserved in peat soils, as seen in Chapter 2. Many of the seeds extracted by the macrofossil analysis sprouted when exposed to light and air, down to a depth of about 80 cm in the peat profile. However, peat swamp forest, which occurs in channelled valley-bottoms and unchannelled valley-bottoms, needs decades to recover from removal.

The third conservation parameter is a possible elevating effect (plug effect), which a peatland can have on the water table of an upper catchment, when the peatland is situated in a lower position of the catchment. For channelled valley-bottoms, this effect is low, since water drains through the channel. In unchannelled valley-bottoms, seeps, and even interdune depression, the water discharge from the catchment passes through the peat body and is decreased and restrained by the lower hydraulic conductivity of the substrate, relative to the dune sands. If these peatlands degrade as a consequence of human use, the peatlands and wetlands in the upper catchment areas will also be affected. Therefore, peatland of these types will gain a high conservation priority for this parameter. Interdune depressions, on the other hand are only a medium priority according to this parameter, as this type of peatland cannot be affected by drainage ditches.

The last conservation parameter is the level of threat each HGMT faces because of climate change. Chapter 5 demonstrated the high vulnerability of interdune depressions and unchannelled valley-bottoms, as a result of which highest conservation priority is given to them under this parameter. Parts of peatlands in channelled valley-bottoms and seeps are also likely to degrade as a consequence of global warming, so that medium conservation priority is accorded to these two types.

The summary of this assessment is given in Table 6-1**.** No weighting of the parameters was applied, due to insufficient background information regarding the scale of importance for each. Unchannelled valley-bottoms with peat swamp forest vegetation (PSF) are the type of peatland, which gains the highest conservation priority. This is followed by unchannelled valley-bottom with reed-sedge vegetation (RS), and channelled valley-bottoms. Peatlands in interdune depressions and peatlands in seeps follow closely behind the last mentioned two. This recommendation, however, should serve only as a guideline. Every peatland has individual hydro-ecological characteristics and should be evaluated carefully.

Table 6-1: Priority of HGMTs for distinct conservation parameters; +++ = high priority; ++ = medium priority; + = low priority; PSF = peat swamp forest; RS = reed-sedge vegetation.

HGTM **Conservation parameter**	**Channelled valley-bottom**	**Unchannelled valley-bottom**	**Interdune depression**	**Seep**
Substrate qualities beneficial to degradation	+++	+++(PSF), ++(RS)	++	++
Regeneration time of natural vegetation	+++	+++(PSF), +(RS)	+	+
Possible positive catchment feedbacks	+	+++	++	+++
Level of thread by climate change	++	+++	+++	++

6.3 Cultivation

In order to adhere to the recommendations for the conservation of peatlands, the wisest measure would be to avoid cultivation. However, this choice does not correspond with the living conditions and necessities of the local people, nor with their rights. Therefore, recommendations need to be given, which conform to the local realities - i.e. which serve to mitigate degradation of peatlands and yet still allow smallholders to sustain themselves.

Peatlands in Maputaland are favoured grounds for cultivation, because other local soils generally consist of dune sand with low field capacities and low nutrient statuses (Grundling A. et al. 2016). Peatlands, on the other hand, are fertile grounds and, unless they are located in interdune depression, their water table can be controlled by drainage ditches to achieve a desired depth. Associated with drainage, however, is the process of peat subsidence (Chapter 4). A farmer who drains a peatland to a depth of 50 cm below the surface level may lose 10-20 cm of peat soil within a few years, and thus she will then need to deepen the drainage ditch again, in order to once again have 50 cm of dry soil. Unless alternative cultivation practices are established, which change the traditional drainage ditch cultivation practice, peatlands will face huge volume losses and degradation within the next decades.

The first recommendation, therefore, is the cultivation of the peatland fringes instead of the peatland centres (Figure 6-2). The nutrient status in the transitional zone between peatland and dune is considerably higher than in the dune soils (Potential cation exchange capacity: *transition zone* = 17 cmol$_c$/kg, with 12% organic matter [N=6]; *dune* = 2 cmol$_c$/kg, with 0.7% organic matter [N=5]; unpublished results from the field campaign 2012). Thus, the transition zone will be able to support a wide range of crops. Pfister (2016) indicates that, of the commonly used crops, the following are capable of growing in the transitional zone: beetroot (*Beta vulgaris)*, cabbage (*Brassica oleracea)*, carrot (*Daucus carota*), cassava (*Manihot esculenta*), cowpea (*Vigna unguiculata*), lettuce (*Lactuca sativa*), maize (*Zea mays*), onion (*Allium cepa*), pepper (*Capsicum sp.*), pumpkin (C*urcubita sp.*), sugar cane (*Saccharum officinarum*) and sweet potato (*Ipomoea batatas*). As the water levels in the transition zone are usually several decimetres below the surface, this puts them in the same range as drained sites.

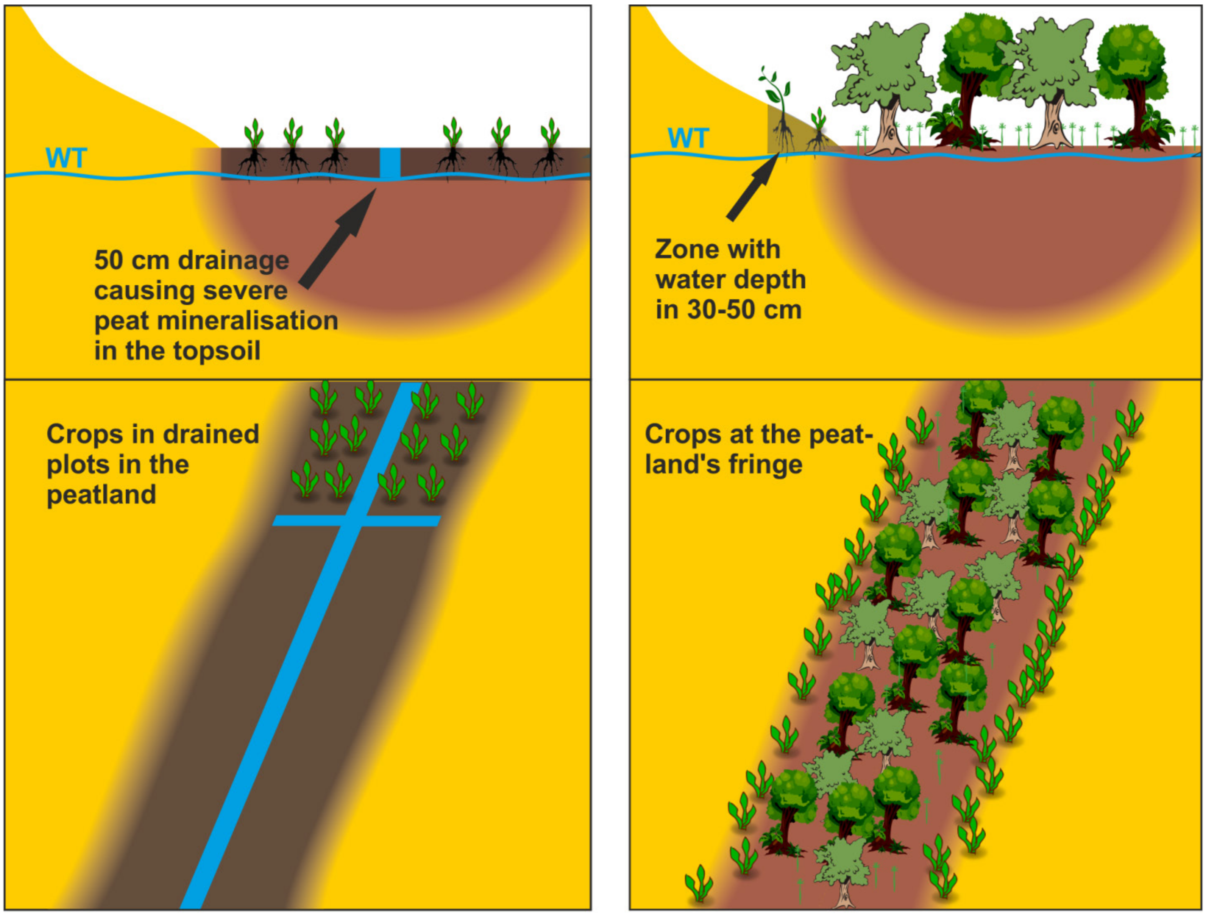

Figure 6-2: Alternative cultivation practice in valley-bottom peatlands. Left: Conventional cultivation in peatland centre with drainage ditches and degraded topsoil. Right: Sustainable cultivation at fringe of healthy peatland.

Even if drainage is not eliminated, the blocking of drainage ditches on a seasonal basis will mitigate peat mineralisation. It should become standard practice to block drainage ditches after the cultivation on a drained peatland is complete, to avoid the subsequent continuation of peat mineralisation.

In interdune depressions, drainage ditches do not work, due to the enclosed shape. Cultivation is usually practiced on raised beds, in order to get 30-50 cm distance between the soil surface and the water level. Organic matter is once again, in this way, exposed to aerobic conditions and subject to mineralisation. Once again a more sustainable way of cultivation is the use of the fringes. As water in interdune depressions cannot drain readily, the risk of inundations is higher here than in other HGMTs. This can badly affect or even destroy the harvest when crops become inundated (see Figure 6-3).

Figure 6-3: Harvest loss due to inundation in the central part of an interdune depression (26°56’47.83’’S, 32°48’57.18’’E). Left: raised bed with sweet potato (Ipomoea batatas) and cassava (Manihot esculenta); picture taken 16 Jan. 2014. Right: raised bed flooded and plants drowned; picture taken 28 Feb. 2014 (pictures do not show precisely the same spot, but both were taken in the central part of the same interdune depression).

To reduce the risk of harvest losses through inundation, cultivation should be adapted to suit seasonal water table fluctuations (Figure 6-4). Before the wet season, the upper part of the transitional zone should be planted with crops which do not need more than half a year to grow to a mature state. After the wet season, the lower transitional zone can be seeded, following the receding water table.

The use of fire to eradicate weeds should be entirely abandoned. Particularly during the dry months from April to September, the risk of peat loss to out of control fires is high. Drained peatlands, with dry surfaces, are prone to this risk even during the wet season. Instead of being burnt, as part of the preparation of the plot, weeds might be cut and put on the surface as mulch, thereby protecting the soil from insolation and loss of humidity.

Paludiculture - the cultivation and harvesting of plants on water saturated peatland soils - should be considered as an alternative to traditional cultivation. Taro (*Colocasia esculenta*), locally known as idumbe, can be cultivated under inundated conditions, if the water is running and therefore providing dissolved oxygen (Onwueme 1999). Therefore, on the fringes of streams in channelled valley-bottoms, the cultivation of Taro is possible without the need to alter the peatlands hydrology. Likewise, without any hydrological alterations being made to the peatland, other non-edible plants have for a long time been harvested for medical uses, weaving products and construction material (Grundling et al. 1998). A good example is the mid-ribs of the leaves of *Raphia* palms, which are a very light and very robust construction material. Fallen palm leaves are collected without harmful consequences for the ecosystem.

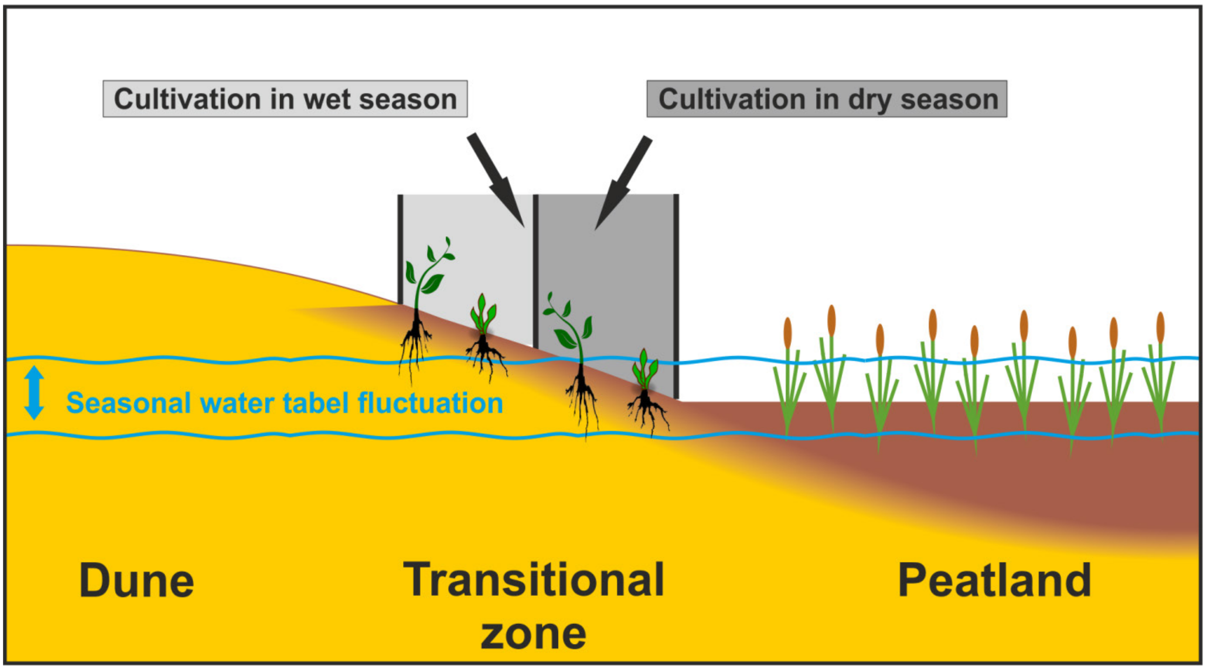

Figure 6-4: Adaptation to seasonal fluctuations at the fringe of an interdune depression: cultivation should move up and down in the transition zone.

Last but not least, melioration of the common arenosols of the dunes can also represent an alternative to subsistence farming on peatlands. Locally little known techniques such as mulching, and the preparation of compost soil from organic household waste are able to enhance soil nutrient statuses, increase water holding capacities, and reduce water losses by evaporation. In addition, they would provide local subsistence farmers with the convenience of establishing plots next to their own houses.

6.4 Restoration

To avoid further peatland losses, the restoration of degraded peatlands should be considered. First of all, the cause of the degradation needs to be removed. If drainage ditches are drying the peatlands surface, they need to be blocked. If a forestry plantation is extracting groundwater next to a peatland, the trees need to be removed. Depending on the degree of degradation, a peatland might be able to restore itself to a state where site-typical vegetation continues to accumulate peat, or - then again - it might not be able to recover, and without further intervention the ecosystem will remain irreversibly changed. In this case, restoration measures might be conducted in order to help to restore the ecosystem to a state close to the natural one - although a complete recovery of its functions might not be possible.

If a peatland is in a minor or medium state of degradation, the reversal of the hydrological deficit should result in self-restoration over the course of the subsequent years. The typical peatland vegetation in interdune depressions, seeps, and also in some unchannelled valley-bottoms consists of radicell peat accumulating Cyperaceae and reed species. If the hydrological conditions of a peatland are reset, this vegetation type is likely to reinstall itself within a season, because many seeds exist in the non-degraded peat, still able to germinate. In addition, many of the species concerned have a hydrological range which allows them to persist even under drier than optimum conditions, alongside new species (Chapter 2). If site typical vegetation does not establish itself, native species which have been identified as peat producers (e.g. *Pycreus polystachyos*, *Cyperus sensilis*, *Cyperus prolifer*) might be introduced (Chapter 2). In peatlands in channelled valley-bottoms and some unchannelled valley-bottoms, where peat swamp forest is the typical vegetation type, reed-sedge vegetation will probably colonise the peatland initially, after hydrological conditions are restored (Chapter 2). Therefore, restoration measures might include the planting of saplings of site-typical trees (e.g. *Voaccanga thouarsii, Syzygium cordatum, Ficus trichopoda*) since this will enhance the re-establishment of peat swamp forest vegetation.

A degraded peatland is beyond the threshold of self-restoration if the altered hydrological characteristics of the affected peat layers do not allow an evenly distribution of water in the peat body after removing the cause of the water deficit. Peatlands with deep earthification horizons and desiccation cracks might not be able to retain water in the surface horizons, even after a drainage channel is blocked (Chapter 4). If the high hydraulic conductivity of cracks and macropores avoid both, the retention of water and the equal distribution of water, in the peatland's surface horizon (Figure 6-5), the implementation of a berm can be considered to retain the water in the peatland (Quinty & Rochefort 2003).

In severe cases of peatland degradation with grainy moorsh horizons as topsoil layers, vegetation has problems to re-establish itself, even after the removal drainage ditches or forestry plantations, because the loose grainy moorsh layer inhibits contact with the compact and humid peat underneath (Quinty & Rochefort 2003). In Maputaland, where the tropical-subtropical climate induces a high potential evapotranspiration, extreme dryness can be the consequence. The partly burnt Vazi peatland complex is such an example, where additionally salinisation and hot surface temperatures create a hostile environment for plants. In this case, the best option for restoration is scraping off the severely degraded surface peat (Quinty & Rocheford 2003). After the removal of the degraded peat, conditions are once again favourable for the typical peatland vegetation, and although it might initially be necessary to reintroduce various species, they will soon recolonise the place.

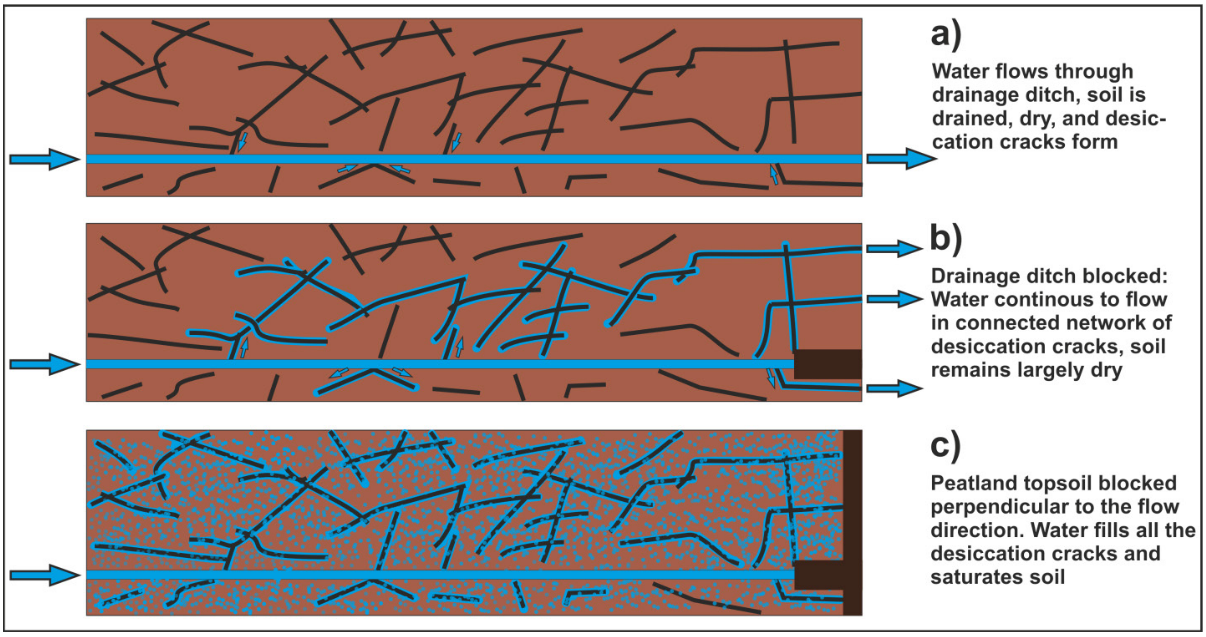

Figure 6-5: Schematic water distribution in a degraded peatland (bird's eye perspective). Blue arrows indicate water flow gradients. **(a)** degraded peatland with active drainage channel;**(b)** degraded peatland with blocked drainage channel; **(c)** degraded peatland with implemented cross-sectional berm in topsoil.

6.5 Further research

In order to develop strategies for the future well-being of peatlands in Maputaland, further research should focus on some crucial points.

A lot more research needs to be carried out to investigate the degradation stages. Soil qualities, and also indicator plant species, should be investigated as proxies for the severity of degradation. The objective must be to evaluate their capacities as proxies for the determination of a tipping point, beyond which the self-restoration of typical peatland vegetation is no longer possible, even after the re-establishment of the appropriate hydrological conditions.

It was observed that increasing degradation lowers C/N ratios and pH-values. This should be investigated to ascertain whether this change in the ecological conditions increases the likelihood of invasion by alien plant species.

In order to develop legislative regulation for buffer widths between peatlands and forestry plantations, threshold distances should be evaluated - for example, through hydrological modelling.

Hydrological modelling could also be used, to further investigate the probable impacts of climate change on the peatlands of the Maputaland Coastal Plain.

Further research might also be done in order to complete the description of botanical peat types in South Africa. In particular, the already known botanical peat types formed by *Prionium serratum, Cyperus papyrus*, *Phragmitis australis* should be described morphologically and test made of their basic soil qualities.

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Appendix 1

Article

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Physical and hydrological properties of peatland substrates from different hydrogenetic wetland types on the Maputaland Coastal Plain, South Africa

Franziska Faul[1]*, Marvin Gabriel[2], Niko Roßkopf[2], Jutta Zeitz[2], Cornelius W van Huyssteen[3], Mathilde L Pretorius[4] and Piet-Louis Grundling[4]

[1] *Faculty of Earth and Environmental Sciences, University of Potsdam, Potsdam, Germany*
[2] *Faculty of Life Science, Humboldt University of Berlin, Berlin, Germany*
[3] *Department of Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein, South Africa*
[4] *Centre for Environmental Management, University of the Free State, Bloemfontein, South Africa*
** Corresponding author, email: faul@uni-potsdam.de*

The Maputaland Coastal Plain in KwaZulu-Natal province is home to 60% of all peatlands occurring in South Africa. These ecosystems are increasingly threatened by unsustainable agricultural utilisation, a growing population and climate change. The aim of the study was, therefore, to investigate wetland type characteristic substrates and their physical properties in order to provide more detailed knowledge about the agricultural impact on them. Six study sites were selected and detailed profile descriptions as well as *in situ* measurements of different physical and hydrological soil parameters were conducted. Soil samples were analysed with laboratory measurements of the saturated hydraulic conductivity, water retention characteristics and hydrophobicity. In addition, the bulk density as well as the organic carbon content were determined. Saturated hydraulic conductivity, hydrophobicity and total water retention capacity were highest for peat derived from wood, which furthermore presented the lowest bulk densities and was found to occur only in channelled and unchannelled valley-bottom wetlands and was absent in interdunal depression wetlands. It was concluded that drainage and clearance of forested valley-bottom wetlands has severe impacts on the physical peat properties. Potential subsidence of low-density peat and consolidation aggravate the danger of flooding and hydrophobicity increases the generation of surface runoff and subsequently the risk of erosion.

Keywords: hydrogenetic wetland type, peatlands, peat substrates, physical properties

Introduction

Peatlands are an important provider of various ecosystem services on a global scale (Kimmel and Mander 2010; Joosten et al. 2012) and within the regional context in northern KwaZulu-Natal (Grundling and Grobler 2005). Peatlands are exposed to threats resulting from inadequate management and utilisation, increasing needs of the continuously growing population and climate change (Joosten et al. 2012). Their physical and hydrological soil properties can yield information regarding the impact of land-use change and drainage (Boelter 1969; Schwärzel et al. 2002; Anshari et al. 2010; Kechavarzi et al. 2010).

The majority of South Africa's peatlands are located on the Maputaland Coastal Plain (MCP) along the country's north-east coast (Grundling et al. 1998). The wetland vegetation provides the organic material for peat accumulation, whereas the vegetation type subsequently affects the physical peat properties (Loxham and Burghard 1986). Peat-forming plants on the MCP are mainly reeds, sedges and grasses (Grundling and Grobler 2005). Peat swamp forests (PSF), however, form another unique and increasingly threatened peatland habitat and represent the second-rarest forest type in the country, of which 75% are located on the MCP (Grobler 2009; Clulow et al. 2013) and 50% are found within the protected area of the iSimangaliso Wetland Park (Sliva et al. 2004). These forested peatlands mainly occur along slightly sloped interdunal drainage lines and are characterised by fluctuating water tables and horizontal water through-flow. The corresponding wetland types are either channelled or unchannelled valley-bottom wetlands (Ollis et al. 2013). Interdunal depression wetlands often lack surface out- and inflow pathways (Ollis et al. 2013). This wetland type is characterised predominantly by grass and sedge vegetation and the absence of trees (Sliva et al. 2004).

Maputaland's peatlands provide a range of ecosystem functions and are important for freshwater storage and filtering, biodiversity and play a vital role in the daily life of local communities (Grundling 2014). Although about 50% of Maputaland's remaining peatlands are located in proclaimed conservation areas, many of them are used by local communities as fresh water, biomass and horticultural resources (Grundling et al. 1998). In approximately 60–80% of Maputaland's PSF areas, cultivation of different crop species has already started a transformation of the swamp forest vegetation as well as an alteration of soil physical parameters (Grobler 2009). The popularity of peat soils for agricultural practices can be explained by the lack of other fertile soils in the area. Surrounding Maputaland's peatlands, leached and fast-draining sandy soils make crop cultivation extremely difficult. Especially channelled valley-bottom wetlands, situated along gentle slopes, are

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easily drained and tillage of peat soils is possible without advanced farming equipment (Grobler 2009).

Drainage and intensive use of peatlands leads to alterations in physical properties of peat soils (Schwärzel et al. 2002). It follows that soil physical and hydraulic properties may serve as indicators of the impact that these human activities have upon peatland ecosystems and enable us to better understand the potential consequences (Schwärzel et al. 2006). Nevertheless, there is a lack of research dedicated to the impacts of peatland utilisation on the physical and hydrological properties of Maputaland's peatlands.

This study focuses on the evaluation of several physical and hydrological properties of peat soils, observed at six study sites with varying land-use intensities, and the subsequent assessment of the three represented wetland types. The goal was to enhance the possibility of assessing wetland type and substrate-dependent impacts of land-use change on these features. The bulk density, water retention, as well as the saturated hydraulic conductivity and wetting properties were measured. An inverse solution technique was applied to determine the water retention curve.

Materials and methods

Study area

The Maputaland Coastal Plain (MCP) stretches out between the latitudes 26° and 28° S and between longitudes 32° and 33° E (Figure 1). Its geographical borders are the uMlalazi River near the town Mtunzini in the south, the Lebombo Mountains in the west and the Indian Ocean in the east. It stretches north to Maputo in Mozambique and covers an area of approximately 9 430 km² (Grundling et al. 2013). Unspecified or subsistence agriculture constitute around 79% of land use. The other 21% are part of protected conservation areas (Grundling et al. 2013).

The coastal plain is characterised by a gently undulating terrain, coastal lake systems and dunes, as well as river-related systems (Porat and Botha 2008). The lake systems include coastal lakes, such as Lake Sibaya and the extremely dynamic estuarine-linked lake systems Kosi Bay and Lake St Lucia (Bruton and Cooper 1980). The soils of the MCP predominantly consist of geologically recent fine-grained aeolian sands and are mostly infertile and low in agricultural potential (Watkeys et al. 1993; Botha and Porat 2007).

The climate of the study area may be classified as subtropical with hot and humid summers and mild winters (Taylor 1991). Annual mean temperatures often exceed 21 °C (Bruton and Cooper 1980). Spatial annual precipitation patterns are extremely variable within the MCP, as there is a strong gradient from 1 000 mm annual rainfall at the coast to around 600 mm further inland and 800 mm along the crest of the Lebombo Mountains (Watkeys et al. 1993). Although annual precipitation is high, especially compared with most other parts of the country, a soil water deficit occurs frequently during dry winter months (Clulow et al. 2012). This is due to the equally high potential evapotranspiration, ranging from 1 300 to 1 500 mm along the cooler coastline and 1 500 to 1 600 mm in the hotter and dryer inland regions (Lubbe 1997).

The inland landscape can be described as a unique combination of different wetland types, occurring between dune cordons, such as floodplains, fens, swamp forests, pans, mangroves and riverine woodlands (Grundling et al. 2014). These systems are predominantly groundwater dependent (Grundling 1998). The peatlands of the MCP vary between approximately 0.5 and 10 m thickness, which results in an estimated resource of moist peat of about 158 million m³ in the region. In total, MCP's peatlands comprise an area of over 20 250 ha, which equals 60% of all peat resources in South Africa (Grundling et al. 1998). Most peatlands found on the MCP were dated to be of Holocene age (Grundling and Grobler 2005). According to Grundling et al. (1998), average accumulation rates for the MCP over the last 7 000 years are found to equal around 1.06 mm y^{-1}.

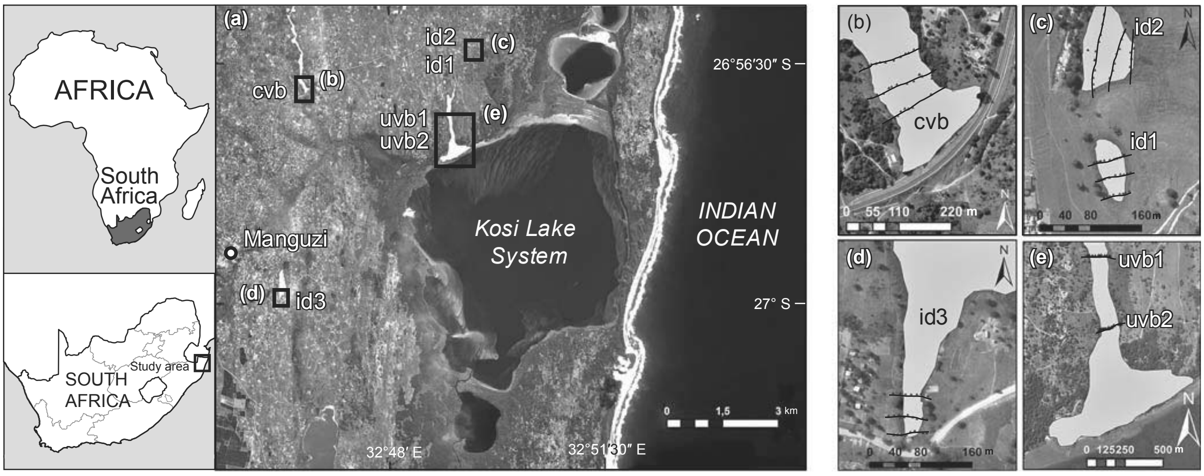

Figure 1: Study area (a) and specific study sites (b–e). Lines and points in (b) to (e) indicate the sampled transects. The satellite image was acquired by LANDSAT in 2008

Ollis et al. (2013) published a classification system for wetlands and other aquatic ecosystems in South Africa, based on that developed by Brinson (1993). The three wetland types investigated in this study are *channelled* and *unchannelled valley-bottom wetlands*, as well as *interdunal depressions*.

Channelled valley-bottom wetlands

A channelled valley-bottom wetland is characterised by a river or stream running through it and is located on the valley floor. The major water input originates from the river channel, either as surface or subsurface flow or as interflow and groundwater inflow from adjacent valley-side slopes. Channelled valley-bottom wetlands are found in longitudinal river zones with steep gradients. On the MCP these wetlands are orientated parallel to the Pleistocene dune ridges and are often linked to coastal lakes with an estuary (Grundling et al. 2000). This wetland type is regarded to be the most common habitat for peat swamp forest vegetation on the MCP (Grobler 2009).

Unchannelled valley-bottom wetlands

These systems are devoid of a channel (stream or river) that runs through the wetland and therefore diffuse water flows prevail. Unchannelled valley-bottom wetlands are located on the valley floor. On the MCP this wetland type is orientated parallel to the Pleistocene dune ridges and is often linked to the coastal lake system or channelled valley-bottom wetlands, into which it drains. Unchannelled valley-bottom wetlands are characterised by gentler slopes and smaller catchments compared to channelled valley-bottoms (Grundling et al. 2012). This wetland type also represents a preferred habitat for peat swamp forest tree species and other plants (Grobler 2009).

Interdunal depression wetlands

Depressions are systems with a closed (or semi-closed) hydrology, surrounded by landforms of higher elevation. The deepest part of a depression is normally found in its centre, were water typically accumulates during rainfall events. In some rare cases, rivers or streams function as additional water sources. Flat-bottomed depressions are often referred to as pans. Interdunal depressions are often connected to the groundwater, in contrast to clay-rich ‘perched’ pans which are not linked to the regional water table (Pretorius 2012). The MCP, however, is also characterised by the impermeable Pleistocene Port Dunford Beds, impeding fast percolation and keeping water tables high (Sliva et al. 2004; Porat and Botha 2008; Grundling 2014). The dominant soils occurring in these depressions also entail peat and the natural vegetation is mainly composed of reeds, sedges and grasses, whereas trees mostly grow along peripheral wetland regions.

Field and laboratory measurements

A number of different *in situ* and laboratory methods were applied in order to describe characteristic profiles of the selected study sites and to determine characteristic soil physical and hydrological properties (Table 1).

Out of numerous potential wetlands, a total of six study sites were selected. The selection was based on the objective of a good representation, including at least two examples of the different investigated wetland types. However, only one channeled valley-bottom wetland was clearly identified and investigated. Depending on the size and shape of the wetland investigated, one to three transects were sampled and described in detail (Table 2). One site-characteristic profile was chosen for each site and was used for further hydrological and physical experiments.

Profile description

Peat profiles were sampled using an Eijkelkamp peat auger, whereas an Edelmann auger was used to sample mineral soils at the outer boundaries of the wetland and at the bottom of a profile. The type of substrate was determined (Table 3). Horizon boundaries were demarcated and defined (Table 4), as well as the soil structure, Munsell soil colour and the degree of peat decomposition (Table 5; von Post 1922). At each site-characteristic profile, measurements of the pH were also made. The soil descriptions were

Table 1: Overview of applied field and laboratory methods. N = repetitions

Characteristic	Unit	N	Method	Reference
Field methods				
Profile descriptions	–	–	Documentation of field observations, according to the German Pedological Mapping Directive KA 5 (Ad-hoc-AG Boden 2005)	Ad-hoc-AG Boden 2005
Peat sampling	–	3	Eijkelkamp peat auger for deep soil samples with 100 cm³ and sample ring for upper peat horizons, with the dimensions $V = h \times r^2$, with h = 5 cm and r = 3.4 ± 0.5 cm	Eijkelkamp (2014)
Laboratory methods				
Saturated hydraulic conductivity (K_{sat})	m s^{-1}	3	Falling-head method (n = 3)	Reynolds and Elrick (2002)
Water retention curve (WRC)	–	3	Up to pF 1.8: hanging water column, from pF 2.0: pressure pot, three-fold repetition, sample volume approximately 80 cm³	Radcliffe and Šimunek (2010)
Bulk density (BD)	kg m^{-3}	3	Thermogravimetrical desiccation at 105 °C	DIN EN 15934: 2012-11
Hydrophobicity	s	3	Water drop penetration time method (WDPT)	Letey (1969); Doerr (1998)
Organic carbon (C_{org})	kg kg^{-1}	3	TruSpec CHN-Determinator (LECO Corporation)	DIN ISO 10964: 1994

conducted according to the German pedological mapping directive (Ad-hoc-AG Boden 2005).

Undisturbed peat samples were taken in the upper horizons at each site characteristic soil profile using PVC sample rings. This was done in irregular depth intervals in the middle of a new horizon. Later, these samples served for further laboratory measurements. In addition, disturbed soil samples were taken for the determination of organic carbon by combustion (DIN ISO 10964) and hydrophobicity, as the soil structure has no impact on these parameter.

Bulk density

The bulk density (BD) was determined by weighing soil samples, after the samples had been dried for 48 h in an oven at 105 °C. The difference between the dried and the wet sample weight in relation to the sample volume was then used to calculate the BD (DIN EN 15934: 2012-11).

Water retention curves

The equilibrium water content for defined pressure heads was realised through drainage of primarily saturated (48 h) soil samples. This drainage was initiated, as a corresponding negative pressure was applied to the liquid phase of the soil-water system. The negative pressure was achieved by connecting a hanging water column indirectly to the sample (Radcliffe and Šimunek 2010). As the water flux through the sample stopped, a hydrostatic equilibrium was achieved and the water content was determined by weighing the soil sample. This method was applied for pF values 0, 0.4, 1.0 and 1.8 (the pF-value is defined as the logarithm of the amount of soil water tension in hectopascals). To determine soil water contents at pF values between 2.0 and 4.2, a pressure membrane apparatus was applied (Radcliffe and Šimunek 2010). The wet soil samples were in contact with a ceramic plate, which allowed water to drain through its micropores, thus leaving the pressure chamber. Compressed air was applied through the inlet tube at the top of the cell, triggering the drainage process.

Fitting the van Genuchten equation

The water retention curve was predicted and fitted to the observed data, using Equation 1 developed by van Genuchten (1980). Weiss et al. (1998) found this model suitable to empirically describe moisture retention curves in peat soils.

The four independent parameters Θ_r, Θ_s, α and n had to be estimated from observed soil-water retention data. The saturated water content Θ_s is easily obtained, whereas the residual water content Θ_r, is defined as the water content of very dry soil, e.g. at the permanent wilting point (pF 4.2).

$$\Theta(h) = \Theta_r + \frac{(\Theta_s - \Theta_r)}{\left[1+(\alpha h)^n\right]^m} \tag{1}$$

The parameter m is defined as $m = 1 - n^{-1}$, with n being a dimensionless shape parameter related to pore size

Table 2: Classification of investigated study sites and further site-specific information

Site ID	Wetland type	Land use	Ecological state	Area (ha)	No. of transects	No. of profiles
cvb	Channelled valley-bottom	Partly cultivated	Degraded / pristine	22.2	3	31
id1	Interdunal depression	Natural reeds and sedge vegetation	Pristine	0.3	3	30
Id2	Interdunal depression	Natural reeds and sedge vegetation	Slightly degraded	0.7	3	26
id3	Interdunal depression	Cultivated	Severely degraded	12.6	3	24
uvb1	Unchannelled valley-bottom	Fallow, succession	Degraded	38.6	1	8
uvb2	Unchannelled valley-bottom	Natural peat swamp forest	Pristine		1	9
Total					14	128

Table 3: Classification of determined fen peat soil horizons according to the German pedological mapping directive KA 5 (Ad-hoc-AG Boden 2005) and Stegmann et al. (2001)

Symbol	Description	Characteristic
nHv	Earthification fen horizon	Topsoil horizon of drained mires; poorly to moderately earthified by aerobic mineralisation and humification; crumb or fine subangular structures
nHa	Aggregation fen horizon	Subsoil horizon, coarse to fine angular blocky structure caused by shrinkage and swelling processes as a consequence of drainage
nHb	Peat accumulating fen horizon	Topsoil horizon with recent dead plant and still completely undecomposed plant material; constantly reduced state (proposed by Stegmann et al. 2001)
nHw	Reductive / oxidative fen horizon	Horizon characterised by altering water tables; at times in a reduced state and during other time periods influenced by oxidative conditions
nHr	Reductive fen horizon	Permanently below the ground- or perched water table and preserved in a reduced state
fFr	Reductive gyttja horizon	Horizon composed of organic deposits and muds; constantly in a reduced state
M	Colluvium	Mineral soil horizon from rearranged, often humus-rich soil material as a result of deforestation and agronomic use of slopes
Gr	Reductive gley horizon	Groundwater-affected horizon of a blue-greyish colour, constantly saturated with water and iron in reduced form (FeII)

distribution. Another shape parameter is α [m^{-1}]. The pressure head is represented by the symbol h [m]. It is negatively related to the matrix potential Ψ, with $\Psi = -h$. Because Θ_r and Θ_s were measured in the laboratory, the two remaining parameters α and n could be estimated using the analytical model of van Genuchten et al. (1991) implemented in the RETC (RETention Curve) computer software (van Genuchten 1991).

Saturated hydraulic conductivity

The *falling head* method was applied to estimate the saturated hydraulic conductivity (K_{sat}). Previously saturated soil samples were tightly connected with silicon and tape to another piece of PVC tube of the same dimensions, inhibiting water leakage. Water was initially ponded within the second tube to a height of $b_1 = 6$ cm above the saturated sample column. It was then allowed to fall with time (t_1) to the height of $b_0 = 5$ cm, as it was flowing through the soil column and out of it at the bottom. The hydrostatic pressure at the soil surface is time dependent, as is the pressure gradient $(L + b)\cdot L^{-1}$, where L determines the vertical length of the soil sample. The water outflow at the bottom of the sample also changes over time and is proportional to the change of pressure head. For such conditions, Darcy's Law may be applied:

$$K_{sat} = \frac{L}{t_1} \ln \frac{b_0 + L}{b_1 + L} \tag{2}$$

Hydrophobicity

For the determination of hydrophobicity the water drop penetration time method (WDPT) was used. The test involves placing a water drop of a specific mass on the surface of a previously dried soil sample and recording the time required for its complete penetration (Letey 1969). As there is no persistency of hydrophobicity but rather a decay of it, the delayed water infiltration reflects the time, during which the surface tension of the soil remains higher than that of the droplet (persistency of hydrophobicity).

Results and discussion

Stratigraphy and properties of profiles

Table 6 summarises the main results and characteristics of the investigated characteristic peat profiles at each study site. Figure 2 primarily shows the horizon dimensions and designation (definitions in Table 3). It indicates that the investigated profiles of channelled and unchannelled valley-bottom wetlands are deeper than the ones of interdunal depression wetlands. It furthermore gives an impression

Table 4: Overview of investigated substrates in this study, according to the German Pedological Mapping Directive KA 5 (Ad-hoc-AG Boden 2005)

Substrate designation	Characteristic
Hnl	Wood peat with normally high degree of decomposition; organic matter: ≥50% dead woody plant material
Hnr	Belongs to sedge peats, composed of fine, hollow, pale grey rootlets/root fragments
Ha	Amorphous peat, without identifiable plant remains and high degree of decomposition; colour: brown to black
Fhg	Detritus or organic gyttja; most frequently occurring limnic sediment; colour: grey to black with slight olive tint
Fms	Organo-mineral limnic sediment, mainly composed of sand with noticeable content of organic matter; colour: grey to black

Table 5: The von Post scale for assessing peat decomposition according to von Post (1922)

Degree of decomposition	State of squeezed liquid	Proportion of peat extruded	Nature of plant residues	Description
H1	Clear, colourless	None	Plant structure unaltered; fibrous, elastic	Undecomposed
H2	Almost clear, yellow-brown	None	Plant structure distinct, almost unaltered	Almost undecomposed
H3	Slightly turbid, brown	None	Plant structures distinct, most remains easily identifiable	Very weakly decomposed
H4	Strongly turbid, brown	None	Plant structure distinct, most remains identifiable	Weakly decomposed
H5	Strongly turbid, contains a little peat in suspension	Very little	Plant structure clear but indistinct and difficult to identify	Moderately decomposed
H6	Mud, much peat in suspension	One-third	Plant structure indistinct but clearer in residue, most remains undefinable	Well decomposed
H7	Strongly muddy	Half	Plant structure indistinct	Strongly decomposed
H8	Thick mud, little free water	Two-thirds	Plant structure very indistinct – only resistant material such as roots	Very strongly decomposed
H9	No free water	Almost all	Plant structure almost unrecognisable	Almost completely decomposed
H10	No free water	All	Plant structure not recognisable, amorphous	Completely decomposed

of the real in-field colours of the substrates by applying the Munsell colour system.

Channelled valley-bottom wetland (cvb)
In contrast to the surface horizons (nHw) composed of wood peat in the natural part of cvb_n, the cultivated part cvb_c indicated earthification and decomposition processes in the upper two peat horizons (nHv), which were composed of amorphous peat (Figure 2). In the cultivated part the horizon composed of wood peat (110–230 cm) was covered by a relic earthification horizon (rHv). The pH value of 4.4 of the surface horizon was lower in the utilised area compared with the natural part where the pH was 5.6. Bulk densities in the cultivated area ranged from 0.14 g cm^{-3} (wood peat) to 0.31 g cm^{-3} (amorphous peat) and were higher than the bulk density of wood peat with 0.10 g cm^{-3} in the natural part. With 9.7 to 56.4 m d^{-1}, the saturated hydraulic conductivity was much higher in the natural area. In the cultivated part it varied between 0.56 and 1.14 m d^{-1}.

Interdunal depression (id)
The stratigraphy of id1 was influenced by fluctuating water tables (nHw) and the physical properties were mainly characterised by the features of radicell peat. The peat layer was rather thin and reached the limnic organic mud deposits already at a depth of 30 cm. The pH values increased from 4.9 at the surface to 5.3 at the bottom of the profile. The bulk density equalled 0.28 g cm^{-3} for radicell peat and K_{sat} ranged from 3.9 m d^{-1} (radicell peat) to 1.9 m d^{-1} (organic mud).

Characteristic for id2 was a currently peat-accumulating horizon (nHb), meaning that the horizon was currently accumulating peat as dead plant material was only weakly decomposed (Table 3). It was present at numerous study points and decreased in thickness towards the edges of the wetland. At the representative profile it ranged from the soil surface up to a depth of 30 cm. It was formed by weakly decomposed radicell peat (H2 and H5) and well-preserved dead roots. The horizon furthermore presented an organic gyttja (limnic deposits) content of approximately 10%. This observation was also made for the following horizon (nHr), reaching a depth of 100 cm. The degree of decomposition here was positively correlated with the soil depth and increased up to H8. The two peat horizons were underlain by a 100-cm-thick horizon (fFr) composed of organic gyttja, followed by 35 cm of sandy gyttja before the dune sand started at 235 cm. The bulk density of the nHb horizon with 0.09 g cm^{-3} was very low. For the nHr horizon a bulk density of 0.15 g cm^{-3} was measured. The pH values ranged from 4.6 to 4.8 in the nHb and nHr horizons and increased with depth to values between 5.0 and 5.1 for the two gyttja horizons. The K_{sat} varied between 5.7 (organic gyttja) and 17.0 m d^{-1} (radicell peat).

The surface horizons of id3 were heavily influenced by aggregation and earthification processes (nHa/nHv) and were composed of amorphous peat. The drained surface horizons were alternated by a 60-cm-thick decomposed (H8–9) nHr horizon, mainly consisting of radicell peat. Covered by 10 cm of organic gyttja and 120 cm of sandy gyttja, the dunal sand was reached at a depth of approximately 225 cm. The pH value of 4.4 of the nHv horizon was the lowest of the profile. Bulk densities of amorphous and radicell peat were high and equalled 0.35 g cm^{-3} and 0.29 g cm^{-3}, respectively. The K_{sat} ranged from 0.08 m d^{-1} (organic gyttja) to 0.18 m d^{-1} (amorphous peat).

Unchannelled valley-bottom wetland
The representative profile of site uvb1 reached the underlying aeolian sand at a depth 465 cm (Figure 2). The

Table 6: Summary of site characteristics and physical properties. Sites: cvb = channelled valley-bottom, id = interdunal depression, uvb = unchannelled valley-bottom. Physical properties: K_{sat} = saturated hydraulic conductivity, n = repetitions, BD = bulk density, WDPT = water drop penetration time, DD = degree of decomposition, C_{org} = organic carbon. Horizons: nHa = aggregation fen horizon, nHv = earthification fen horizon, nHb = peat-accumulating fen horizon, nHw = reductive/oxidative fen horizon, nHr = reductive fen horizon, fFr = reductive gyttja horizon. Substrates: Ha = amorphous peat, Hnr = radicell peat, Hnl = wood peat, Fhg = organic gyttja, Fms = sandy gyttja

Site	Vegetation cover	Horizon	Substrate	Depth (cm)	n	Median K_{sat} (m d^{-1})	Mean K_{sat} (m d^{-1})	BD (g cm^{-3})	WDPT (s)	DD	pH	C_{org} (g kg^{-1})
cvb	Peat swamp forest	nHr	Hnl	23	3	56.4	52.5	0.10	–	5.0	5.7	–
	Crops (extensive)	nHa	Ha	18	3	1.1	1.4	0.31	–	–	–	–
		nHr	Hnr	43	3	0.9	1.1	0.14	–	–	–	–
id1	Sedges	nHr	Hnr	33	3	3.9	3.7	0.28	–	9.0	5.2	–
id2	Sedges and reeds	nHb	Hnr	30	3	17.0	33.7	0.09	4	3.5	4.6	358.0
		nHr	Hnr	60	3	9.9	13.8	0.15	80	6.5	4.8	263.0
		nHa	Ha	12	3	3.3	4.6	0.31	8	10.0	4.0	173.0
		fFr	Fms	45	3	5.3	5.3	1.39	2	–	4.2	24.4
		nHa	Ha	10	3	1.5	1.8	0.47	–	10.0	–	–
id3	Crops (intensive)	nHa	Ha	18	3	0.2	0.2	0.35	479.0	9.5	4.4	–
		nHr	Hnr	43	3	0.2	0.3	0.30	–	–	–	–
		fFr	Fms	103	3	0.1	0.4	1.55	0.5	–	6.0	–
uvb1	Sedges and reeds	nHr	Hnr	25	3	3.4	3.4	0.15	5 820	7.5	4.7	486.5
		nHr	Hnl	40	3	2.4	3.7	0.11	5 831	6.5	–	486.5
uvb2	Peat swamp forest	nHw	Hnr	10	3	5.5	32.8	0.11	2 096	6.0	4.8	444.5
		nHr	Hnl	30	3	60.1	74.8	0.08	13 720	4.5	5.0	453.0
		fnHv	Ha	30	3	5.7	4.9	0.19	–	10.0	–	–
		fFr1	Fhg	40	3	0.6	3.4	0.33	–	–	–	–

upper horizon, which was classified as a currently peat-accumulating fen horizon (nHb), was composed of radicell peat and covered by a 5-cm-thick root felt. Beginning at a depth of 30 cm, relatively little-decomposed wood peat (H4–5) of a lighter and slightly reddish colour formed the following horizon with a thickness of 60 cm. From a depth of 60 cm downwards the degree of decomposition increased to H8–9. It then transitioned into a less-decomposed reductive fen horizon, a mixture of radicell and wood peat. With increasing depth, a typical sequence of altering layers of organic gyttja and wood peat was characteristic until the sand content increased and the substrate composing the deepest horizon (350–465 cm) was classified as sandy gyttja. The bulk density decreased from 0.15 to 0.11 g cm^{-3} in the 20–30 and 30–90 cm depths below the soil surface, respectively. The measured pH value fluctuated between 4 in the upper horizons and 5.5 at the bottom of the profile. The median K_{sat} ranged from 3.4 m d^{-1} (in 25 cm) to 2.4 m d^{-1} (in 40 cm).

The profiles drilled and investigated at uvb2 were often covered by a thick litter layer of leaves and branches. At the top of the profile, the first horizon composed of radicell peat (nHw; 0–20 cm) was influenced by fluctuating water tables, indicated by decomposition processes. In the nine profiles drilled along the transect through uvb2, horizons were generally characterised by a reddish-coloured typical sequence of horizons composed of wood peat, followed by horizons composed of organic gyttja. The degree of decomposition estimated for the peat substrates ranged from H3 to 6. The wood peat horizons were characterised by additions of radicell peat and organic gyttja, whereas larger and relatively well-conserved pieces of wood and vertically aligned dead roots were present in the gyttja-composed horizons. The measured bulk density was lower compared with site uvb1 and decreased from 0.11 g cm^{-3} in the nHw horizon to 0.08 g cm^{-3} in the following nHr1 horizon (20–105 cm) composed of wood peat. The pH value increased from 4.8 in the topsoil to 5.6 at depths of 325 to 365 cm. The saturated hydraulic conductivity at this site was characterised by variations, typical for the alternating layers. Values ranged from 0.6 m d^{-1} for organic gyttja and 5.7 m d^{-1} for amorphous peat at the edge of the wetland, and 5.5 m d^{-1} for Hnr and 60.1 m d^{-1} for Hnl in the peatlands centre.

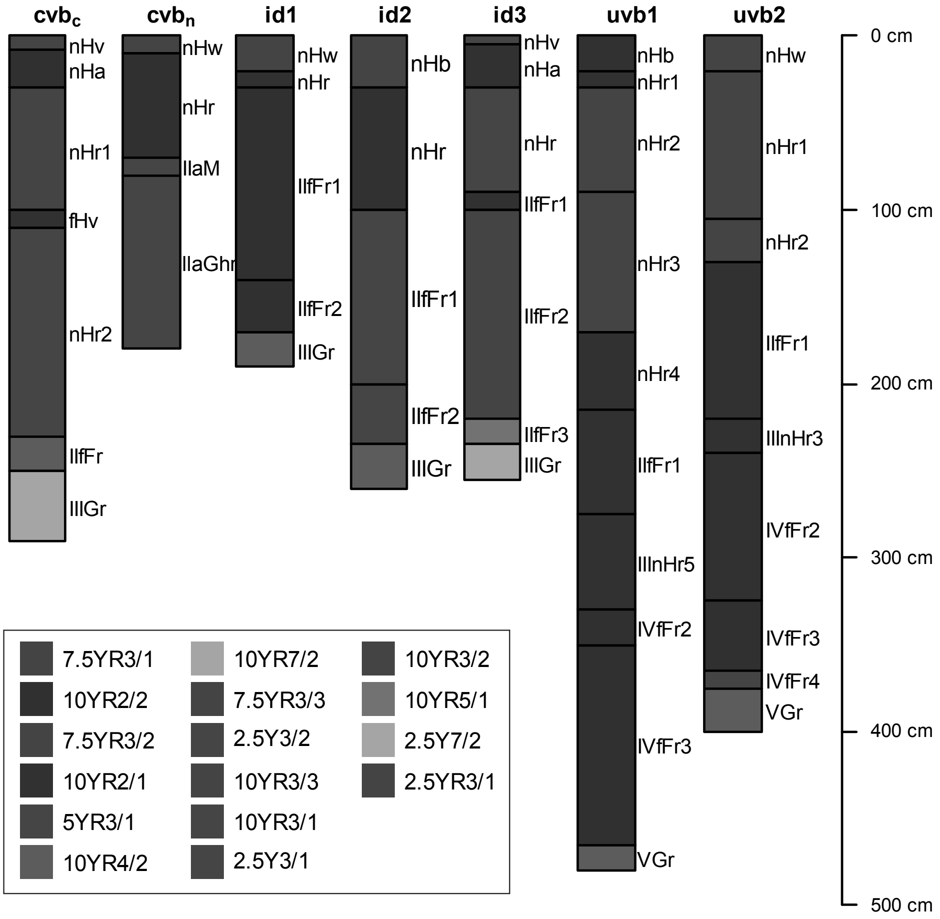

Figure 2: Characteristic soil profiles of all study sites with horizon designations and colours set according to the Munsell colour scheme. For site abbreviations see Table 2 and and for horizon designations see Table 3. cvb_c = cultivated part of cvb, cvb_n = pristine part of cvb

Substrate properties

Bulk density and water retention

The wood peat samples collected for laboratory analysis had the lowest bulk densities, followed by radicell peat, amorphous peat, organic gyttja and sandy gyttja (Table 7).

The parameters of the water retention curve (WRC) obtained for different peat and gyttja substrates differed slightly and only the curve for sandy gyttja indicated distinct characteristics (Figure 3). Differences were observed in the water content range, in which water is available for plants between the pF values 1.8 and 4.2. For radicell peat, the amount of plant available water (66.7 V/Vol%) was very high. This was followed by organic gyttja, wood peat, amorphous peat and sandy gyttja with 64.7, 64.6, 61.9 and 37.0 V/Vol%, respectively (Table 8, Figure 3).

Furthermore, differences in the volume of gravitational water, defined as the quantity of water between full saturation and the water content at pF 1.8, were observed. It was especially high for horizons composed of wood peat (26.1 V/Vol%) and decreased continuously from radicell peat to amorphous peat, to organic gyttja and sandy gyttja (Table 8). In radicell-peat-dominated horizons approximately 7 V/Vol% less water than in wood-peat-dominated horizons drained from the soil until pF 1.8. Amorphous peat and organic gyttja showed similar characteristics, as the average gravitational water loss was 16.3 and 17.1 V/Vol%, respectively. The average volume of water leaving the sandy gyttja between pF values 0 and 1.8 equalled 6.1 V/Vol%. The ratio between the gravitational water and the total amount of plant-available water serves as an indicator for the potential impact of drainage. At 29%, this ratio was highest for wood peat. For radicell peat, amorphous peat and organic gyttja this ratio equalled 21–22%. Sandy gyttja indicated the highest water-holding capacity until pF 1.8 and drained 14% of the plant-available water.

Using the van Genuchten model, the highest water content at the permanent wilting point was calculated for amorphous peat with 27.1 V/Vol%, followed by organic gyttja, radicell peat, wood peat and sandy gyttja with 23.6, 21.6, 18.6 and 10.5 V/Vol%, respectively. The measured mean values are lower and can be taken from Table 8.

Wood peat samples presented the highest saturated moisture contents (Θ_s) with an average of 96.4 V/Vol% and a very low mean residual water content (Θ_r) of 5.7 V/Vol%. The range between Θ_r and Θ_s was smaller for radicell and amorphous peat with average saturated water contents of 94.0 and 91.9 V/Vol% and average residual water contents of 8.5 and 13.8 V/Vol%, respectively (Table 8).

Table 7: Bulk density (BD) of all representative profiles of different substrates. *n* = repetitions, σ = standard deviation, Hnl = wood peat, Hnr = radicell peat, Ha = amorphous peat, Fhg = organic gyttja, Fms = sandy gyttja

Substrate	*n*	Mean BD ($g\ cm^{-3}$)	Median BD ($g\ cm^{-3}$)	σ ($g\ cm^{-3}$)	σ (%)
Hnl	12	0.11	0.11	0.04	32.4
Hnr	18	0.18	0.15	0.09	52.7
Ha	14	0.32	0.31	0.09	29.7
Fhg	3	0.33	0.36	0.11	34.7
Fms	6	1.47	1.49	0.16	10.5

The high saturated water contents and low residual water contents of wood peat samples may be attributed to the degree of decomposition. Gnatowski et al. (2010) calculated the WRC for a number of wood, herbaceous and moss peat samples taken in the valley of the Biebrza, Poland. The authors linked water-retention characteristics of peat soils to their degree of decomposition and found some correlation. Wood peat is generally highly decomposed (Eggelsmann 1990), which partly stands in contrast to some results of this study, as several wood peat horizons indicated lower degrees of decomposition on the MCP. However, it has become apparent during field investigations that applying the von Post method for wood peat may be difficult and lead to incorrect estimations of the degree of decomposition.

Another important factor is the noticeable shrinkage of peat samples that occurs during drying. Consequently, Θ_r at high pressure levels may be underestimated by a few percentage points, because the end volume was smaller than the starting volume, which was used to compute the respective water content. According to the observations of Schwärzel et al. (2002), who focused on horizon characteristics, shrinkage behaviour of peat is dependent on the degree of decomposition. The authors observed that strongly earthified horizons (nHm) start to shrink noticeably at pF 3.5, whereas aggregated horizons (nHa) significantly reduce in volume at pF 3.0 and peat samples from deeper, less decomposed nHr horizons show shrinkage as early as pF 1.8. Shrinkage processes therefore may be especially important for barely decomposed peat with a high proportion of coarse pore spaces. When shrinkage processes are also taken into account, volumetric water contents at high water tension would probably be substantially higher, especially for less-degraded peat. Consequently, this would also lead to estimations of a higher proportion of fine pores.

High water contents at saturation may also be partly explained through oversaturation of the laboratory samples, as the peat can swell beyond field volume if too much water

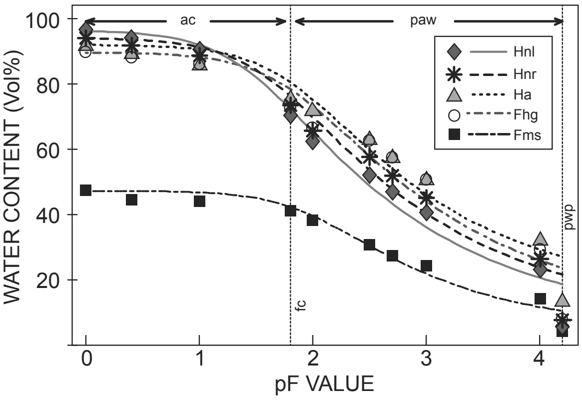

Figure 3: Fitted water retention curves (after van Genuchten 1980) of different substrates. ac = air capacity, paw = plant-available water, fc = field capacity, pwp = permanent wilting point, Hnl = wood peat, Hnr = radicell peat, Ha = amorphous peat, Fhg = organic gyttja, Fms = sandy gyttja

is added to cause saturation. Sometimes, this may even lead to water contents of $\Theta_s \geq 100$ V/Vol%, which of course is not possible (Price et al. 2008).

According to Kechavarzi et al. (2010), the use of the van Genuchten closed-form equation is limited to rigid soils, as the volumetric water content relates water volume to bulk soil volume. The bulk soil volume for compressible peat soils, however, is not constant but changes with altering water contents. Schwärzel et al. (2002) state that especially high water tensions can cause misinterpretations of the pore size distribution due to shrinkage processes. Substantially higher water contents at high pF values (large negative pressure heads) were reported by Schwärzel et al. (2006) when shrinkage was taken into account.

Shrinkage and changes in peat volume during the measuring process were not recorded in the course of this work. Especially wood peat samples, however, demonstrated a severe loss of volume. Although the initial water-storage capacity of wood peat was observed to be high, the loss of water during drainage was higher than for degraded peats, which is partly due to its propensity to shrink and the high proportion of coarse pores (Table 8). A low degree of decomposition implies faster drainage under lower water potentials compared with more-decomposed peats. Drainage and agricultural use leads to aeration and concomitant decomposition, which results in the degradation of soil structure, a loss of void ratio and a decrease in water storage, water transmission and water retention.

Saturated hydraulic conductivity

The hydraulic conductivity under saturated conditions (K_{sat}) was highest for wood peat, followed by radicell peat, organic gyttja, amorphous peat and sandy gyttja, respectively (Table 9).

Research conducted on saturated peat hydraulic conductivities in the Northern Hemisphere is often an order of magnitude lower than the values observed in this study. Wallage and Holden (2011) estimated K_{sat} for natural, drained and restored blanket peat to be 0.92, 0.85 and 1.35 m d^{-1}, respectively. Saturated hydraulic conductivities published by Verry et al. (2011) vary between 0.004 (decomposed peat) and 32.92 m d^{-1} (undecomposed sphagnum peat) depending on the peat substrate and degree of decomposition. Values found for sedge (comparable to radicell peat) peat equalled 11.06 and 0.01 m d^{-1} for slightly decomposed and moderately decomposed peat, respectively. Baird et al. (2004) observed rather high K_{sat} values varying between 1.21 and 25.92 m d^{-1}, which were estimated for the root mat (predominantly composed of *Cladium mariscus* and *Phragmites australis*) of a temperate fen.

The published research providing data on K_{sat} of tropical peatlands is limited and even less concerning tropical peat swamp forest hydraulic conductivity. However, Page et al. (2009) state that in peat swamp forests, hemic and fibric remains of trees result in a larger and more open pore structure and lead to higher hydraulic conductivities than those observed for temperate peat. According to their research in South-east Asia, the hydraulic conductivity of subsurface tropical peat is typically more than 10 m d^{-1}. Kelly et al. (2014) investigated the saturated hydraulic conductivity of three forested peatlands in the Peruvian Amazon. The majority of their published K_{sat} values vary between 0.86 and 17.28 m d^{-1}. Hoekman (2007), who studied tropical peat swamp forests in Kalimantan through mainly satellite radar observation, published an extremely high K_{sat} value of 198.72 m d^{-1}, but gave no details on how this estimate was obtained.

The high conductivity of wood peat calculated in this study, on the one hand, may be traced back to a great abundance of macro pores and, on the other hand, may be induced by recent, still relatively little decomposed plant material, such as twigs and branches altering the soil structure and forming preferential flow paths.

Hydrophobicity

This study provides the first results of hydrophobicity measurements of peatland substrates in South Africa (Table 10). Wood peat (Hnl) samples presented very long

Table 8: Pore size distribution (V/Vol%) of all representative profiles, derived from water retention curves for different substrates. PV = total pore volume, WCP = wide coarse pores (>50 μm), NCP = narrow coarse pores (10−50 μm), MP = meso pores (0.2−10 μm), FP = fine pores (<0.2 μm), Hnl = wood peat, Hnr = radicell peat, Ha = amorphous peat, Fhg = organic gyttja, Fms = sandy gyttja

Substrate	Statistical parameter	PV (pF 0)	WCP (pF 0–1.8)	NCP (pF 1.8–2.5)	MP (pF 2.5–4.2)	FP (pF 4.2)
Hnl	Median (V/Vol%)	96.4	26.1	18.1	46.6	5.7
	N	12	12	12	8	8
	σ (V/Vol%)	2.1	9.5	11.2	10.8	1.3
Hnr	Median (V/Vol%)	94.0	18.8	15.7	51.0	8.5
	N	27	27	27	21	21
	σ (V/Vol%)	2.8	6.5	4.0	7.5	2.8
Ha	Median (V/Vol%)	91.9	16.3	12.5	49.4	13.8
	N	14	14	14	11	11
	σ (V/Vol%)	3.3	5.1	4.6	4.9	4.4
Fhg	Median (V/Vol%)	89.9	17.1	9.9	54.8	7.8
	N	3	3	3	1	1
	σ (V/Vol%)	2.0	4.7	3.3	–	–
Fms	Median (V/Vol%)	47.3	6.1	10.5	26.6	4.1
	N	6	6	6	2	2
	σ (V/Vol%)	6.6	1.2	8.7	12.2	1.8

WDPT with a mean of 3 700.9 s (≈1 h) but a median value of 75 s (≈1 min) and a high standard deviation (σ = 160%). The sample size of five measured Hnl samples was quite small. The seven analysed radicell peat samples showed a lower mean WDPT of 1 639.9 s (≈27 min) and a higher median WDPT of 1 236 s (≈20 min). Although the sample size was larger, the standard deviation of 122% was still very high. The sample size of amorphous peat was also very small, prohibiting the determination of the standard deviation. The measured mean WDPT for this substrate equalled 243.5 s (≈4 min). Organic gyttja entailed a mean WDPT of 410.6 s (≈7 min) and a median WDPT of 60 s (1 min). It reacted slightly hydrophobic (Bisdom et al. 1993), whereas sandy gyttja showed hydrophilic behaviour with very short WDPT (Table 10).

There were a number of outliers in this unique data set of peat hydrophobicity for South Africa. For instance, one sample of site id2 (Hnr) indicated a hydrophilic behaviour with a WDPT of only 4 s (Table 4.1), which could be connected to the properties of a currently peat-accumulating horizon (nHb). Such horizons contain a high share of only slightly decomposed plant material and coarse structures, indicating air-filled gaps within the soil structure, which may facilitate water infiltration into the sample.

On the other hand, penetration may be inhibited completely in some rare cases. As the surface of dry radicell and wood peat is rough and uneven, the contact area between water and soil is reduced, as well as the forces of attraction between particles and water molecules, due to the surface tension of water.

An additional characteristic of hydrophobicity measurements is suggested by the results, in that the longer it took for the water drop to penetrate into the soil, the higher the variance between individual measurements. A very high variability of measured WDPT was observed for wood peat (Hnl; fastest WDPT = 46 s, longest WDPT = 13 721 s, ≈8 h). Regarding the WDPT method in general, it cannot be completely ensured that especially for long WDPT, evaporation was prevented. A glass vessel was placed upside down over very water repellent samples. However, it is still questionable whether evaporation could be completely avoided. This would entail implications for the determination of WDPT. Water drop masses, reduced by evaporation, will cause surface tension forces to outweigh gravitational forces, extending WDPT.

Szajdak and Szatylowicz (2010) applied the same WDPT method and investigated hydrophobicity properties of peat soils in Poland. Their results indicated WDPTs ranged from 63 to 1 986 s. These authors classified almost all peat samples as strongly water-repellent. The sedge–moss samples, with characteristics comparable to the wood peat samples of the present study, presented a severely hydrophobic behaviour and the range of their results is consistent with this study. Water repellencies of boggy peat soils were also determined by Lachacz et al. (2009), who measured the WDPT of 276 soil samples with varied organic matter content. A total of 33 samples had WDPT higher than 900 s and 23 samples had a very high degree of water repellency with WDPT between 3 600 and 18 000 s. The highest WDPT value (16 390 s) was reported for alder peat samples (with 41.9% organic carbon content), a value even higher than the maximum WDPT measured in the present study.

Synthesis of results

Figure 4 visualises correlations between different soil physical and hydrological parameters measured at site-characteristic profiles.

Along the diagonal from the top left to the bottom right of the figure, histograms reveal the data distribution of each parameter. All parameters are plotted against each other in the left triangle of the figure below the diagonal. In the first column to the left, from top to bottom, the saturated hydraulic conductivity is plotted against the mean degree of decomposition (DD), the organic carbon content, the bulk density (BD) and the hydrophobicity. In the bottom line the hydrophobicity is plotted against all other parameters, respectively. The numbers appearing in the upper right above the diagonal represent the respective ρ correlation coefficients (calculated after Spearman, 1 = high positive correlation, 0 = no correlation and −1 = high negative correlation). The dashed lines indicate linear regression models, plotted to demonstrate direction and intensity of the relationships. The organic carbon content was positively correlated with the hydrophobicity (ρ = 0.55). The bulk density increased with a higher DD, which was reflected in the high positive correlation (ρ = 0.96) of the parameters BD and DD. As pore volume reduced with DD, the K_{sat} decreased with higher DD (ρ = −0.63) as well as with higher BD (ρ = −0.84). The K_{sat} was also negatively correlated with the determined hydrophobicity (log[WDPT]; ρ = −0,64). However, only the correlations between K_{sat} and BD, and between DD and BD were statistically significant with *p*-values of 2×10^{-3} and 3×10^{-5}, respectively. In summary, the data reveal that a high degree of decomposition indicates high bulk densities and low saturated hydraulic conductivities.

Table 9: Saturated hydraulic conductivity of all representative profiles of different substrates. *n* = repetitions, σ = standard deviation, Hnl = wood peat, Hnr = radicell peat, Ha = amorphous peat, Fhg = organic gyttja, Fms = sandy gyttja

Substrate	*n*	Mean K_{sat} (m d^{-1})	Median K_{sat} (m d^{-1})	σ (m d^{-1})	σ (%)
Hnl	12	33.0	9.0	41.6	79.4
Hnr	15	17.7	5.8	26.9	65.9
Ha	14	2.7	1.8	2.9	90.4
Fhg	3	3.4	0.6	4.8	69.4
Fms	5	2.2	0.2	4.3	51.7

Table 10: Hydrophobicity of all representative profiles of different substrates. *n* = repetitions, σ = standard deviation, Hnl = wood peat, Hnr = radicell peat, Ha = amorphous peat, Fhg = organic gyttja, Fms = sandy gyttja

Substrate	*n*	Mean WDPT (s)	Median WDPT (s)	σ (s)	σ (%)
Hnl	5	3 700.9	75.0	5 932.5	160.3
Hnr	7	1 639.9	1 236.0	2 005.5	122.3
Ha	2	243.5	243.5	-	-
Fhg	5	410.6	60.0	811.3	197.6
Fms	4	1.4	1.5	0.8	57.1

Consequences and implications of peat properties for peatland utilisation

Wood peat was only found in channelled and unchannelled valley-bottom wetlands. Especially in forested subtropical peatlands, where the remains of trees represent the major peat-forming plant material, degradation and peat decomposition may have severe consequences (Price et al. 2008). This was shown by the wood peat samples collected from study sites cvb, uvb1 and uvb2, which presented very low bulk densities and high saturated water contents, especially when compared with radicell and amorphous peat samples. Peat profiles from the forested peatlands (cvb, uvb1 and uvb2) were also the deepest of all investigated sites, emphasising their importance for landscape water retention. Personal laboratory observations furthermore suggest that wood peat entails a huge propensity to shrink in the course of drying.

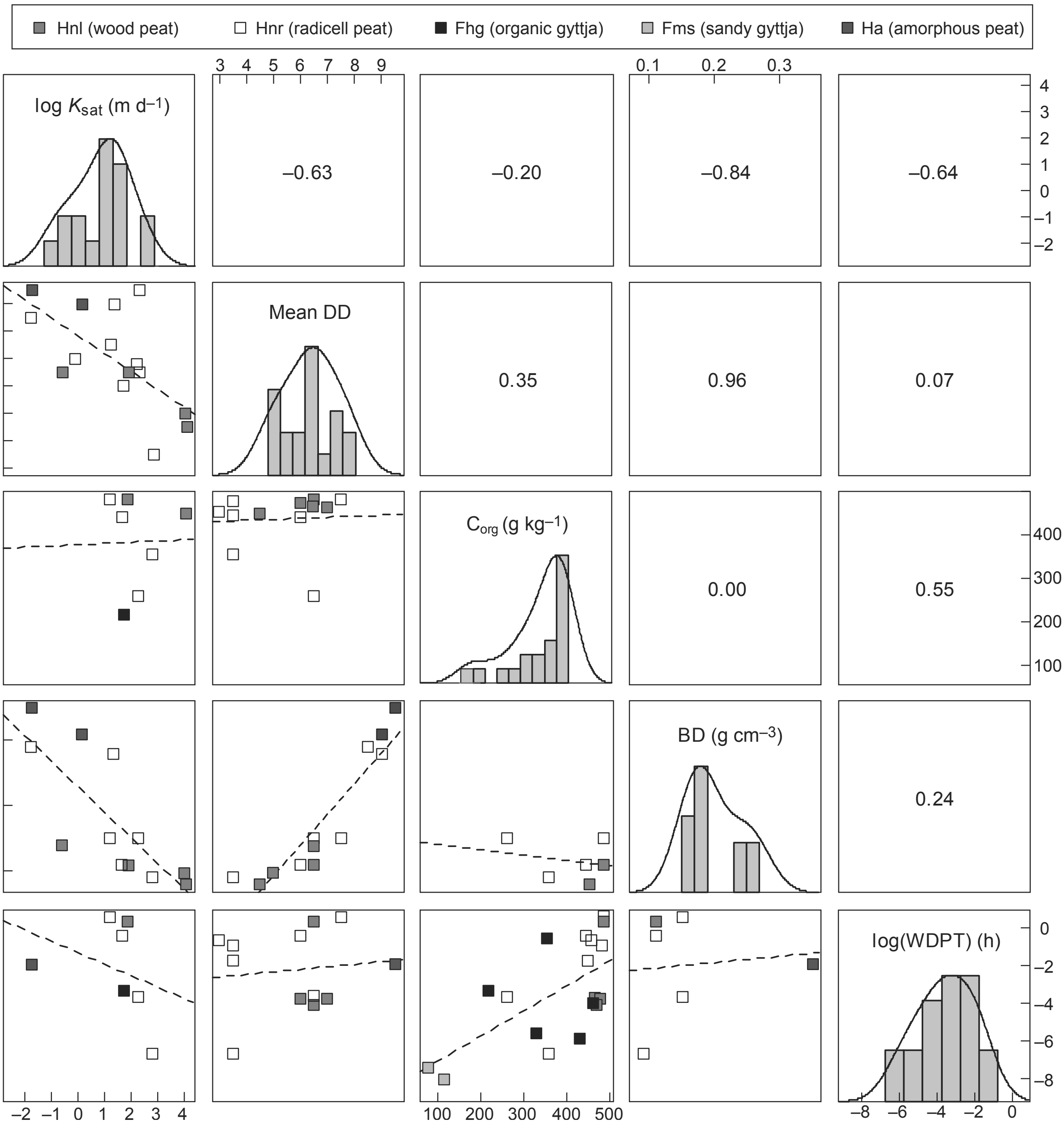

Figure 4: Correlation between different physical and chemical soil properties. Values in boxes above the diagonal are Spearman correlation coefficients. Dashed lines indicate the linear regression model. log(K_{sat}) = logarithmic saturated hydraulic conductivity, DD = mean degree of decomposition, C$_{org}$ = content of organic carbon, BD = bulk density, log(WDPT) = logarithmic water drop penetration time

The impact that drainage has on soil physical and hydrological properties of peat seems to be most serious in peat swamp forest wetlands, additionally impeding sustainable agricultural use from an ecological and economic perspective. During the wet season, substantial precipitation and high rainfall intensities may aggravate the occurrence of floodings at these sites, as cultivation and drainage have started peat subsidence, oxidation and consequent compaction.

Agricultural utilisation of forested wetlands often implies the clearance of the tree cover. The removal of shade-providing peat swamp forest leads to a number of additional consequences to those discussed above. The remaining exposed peat surface has a lower albedo and acts as a heat sink, promoting higher soil evaporation rates and thus the drying of the exposed peat surface (Zeitz and Velty 2002). Recalling the hydrophobic behaviour of dried wood peat, this may have further severe effects, additionally impairing potential restoration measures. When the protection of trees and its litter is missing, the bare peat surface is prone to erosion by wind and water, especially in channelled and unchannelled valley-bottom wetlands, where down-slope water movement occurs during rainfall events. The low bulk densities, observed for wood peat, may furthermore cause peatland subsidence when drained. Shrinkage and peat decomposition during the course of drying is known to be most severe for low-density peat (Schwärzel et al. 2006). This could imply an increased risk of flooding and yield losses if management and utilisation practices are not adapted. The high saturated hydraulic conductivity and low water-holding capacity of gravitational water have further implications for agricultural usage. When drained, plants will potentially struggle to obtain enough water from the soil, as much of the soil water has percolated to the lowered groundwater table.

Conclusions

It has long been established that peatland utilisation alters the physical and hydrological properties of peat soils (Joosten and Clarke 2002; Schwärzel et al. 2002; Kechavarzi et al. 2010; Wallage and Holden 2011; Könönen et al. 2015). Anthropogenic-induced secondary soil development increases bulk density, lowers saturated hydraulic conductivity and reduces the total pore volume and the associated water-retention capacity (Zeitz and Velty 2002; Kechavarzi et al. 2010). Furthermore, changes in the pore size distribution can be observed. The total proportion of wide and narrow coarse pores also decreases. Hence, the volume of gravitational water leaving the soil by drainage is also reduced. Even though pedogenetically altered peat has a larger water-retention capacity at low pressure levels, the water is not completely available for plants, as it contributes also to the greater amount of dead water, stored and held back in degraded peat soils.

Radicell peat, which was the dominant peat substrate found in interdunal depression wetlands, has different physical and hydrological properties than wood peat, which exclusively occurred in channelled and unchannelled valley-bottom wetlands. The mean hydraulic conductivities measured for wood peat were very high in comparison to radicell peat and amorphous peat (33 m d^{-1} vs 17.7 m d^{-1} and 2.7 m d^{-1}, respectively; Table 9). These findings correlate with current scientific literature on tropical peat swamp forests and their hydrological and physical properties (Hoekman 2007; Page et al. 2009; Kelly et al. 2014). Wood peat was also observed to have higher saturated water contents compared with radicell peat and amorphous peat. Wood peat furthermore presented the lowest bulk densities and the most severe hydrophobicity. These findings, in combination with the hydrological connection of channelled and unchannelled valley-bottom wetlands to the various lake systems of the MCP and the thickness of present peat layers, emphasise their crucial importance within the water cycle, including freshwater storage and release during dry seasons. They also imply dangers and risks associated with drainage and agricultural utilisation of these two wetland types, such as peatland subsidence, flooding and erosion.

The measured saturated hydraulic conductivity indicated a high variance, especially for fast-draining wood peat samples. Standard deviations of other parameters were also high. For future research it is therefore recommended to enlarge the sample size of all parameters, in order to verify the results of this study. The quantification of substrate-dependent shrinkage degrees during the process of desiccation represents another open task. Finally, sustainable peatland utilisation concepts have to be developed on the basis of these findings and communicated to the local population.

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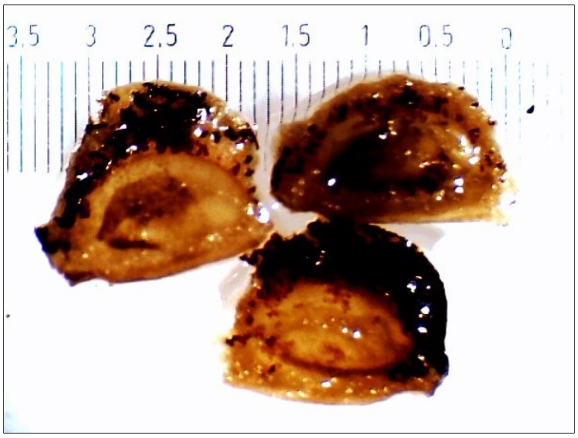
Appendix 2

Images of identified and unidentified macrofossils

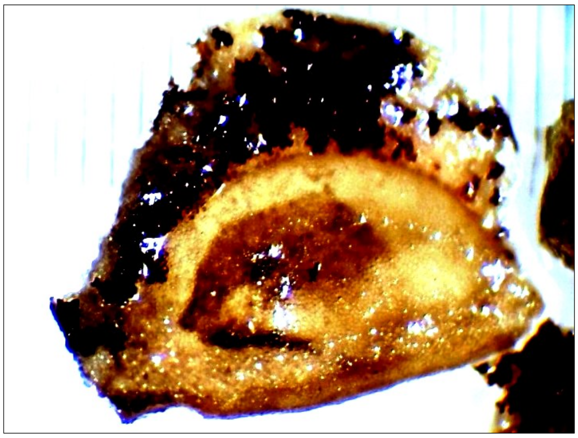
List of identified macrofossils

Picture of fossils with focus on the scale (in mm)

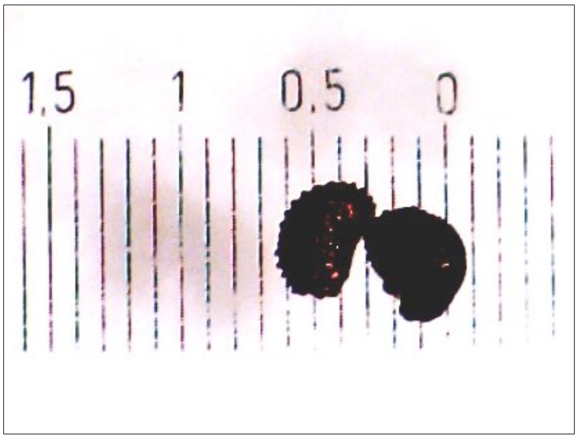
Picture of fossils with focus on colour and surface



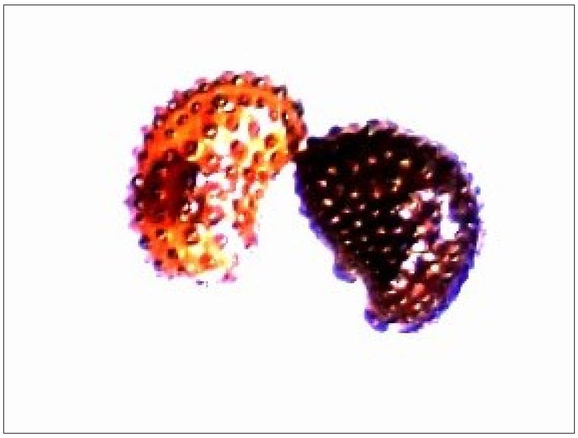
cf. Callitricheae (fruits)



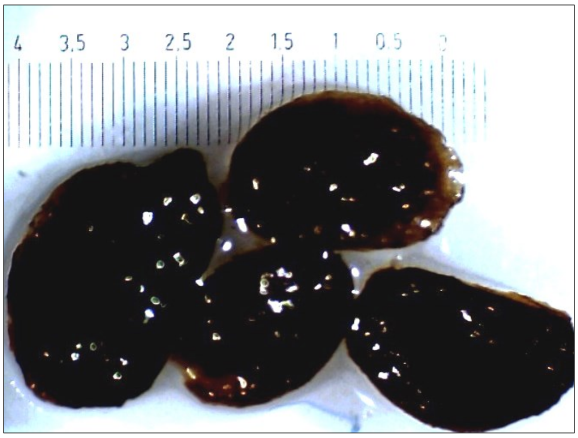
cf. Callitricheae (fruits)



cf. Caryophyllaceae (seeds)



cf. Caryophyllaceae (seeds)

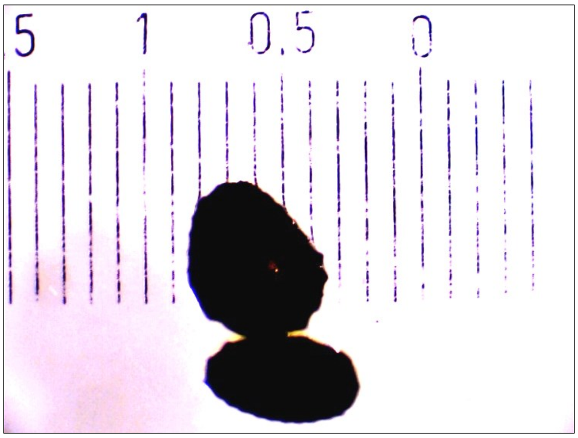


Centella asiatica (fruits)

Centella asiatica (fruits)

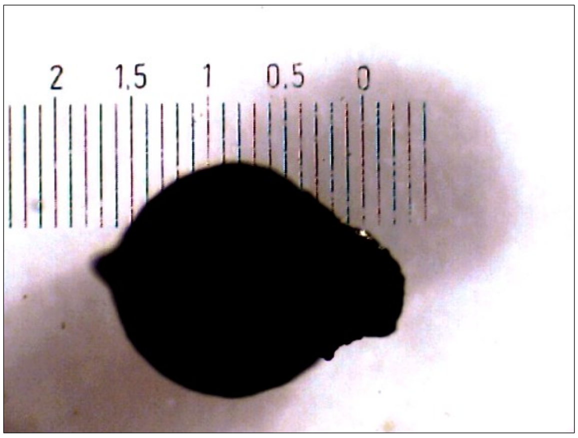
Picture of fossils with focus on the scale (in mm)

Picture of fossils with focus on colour and surface



Chara sp.(oospores)

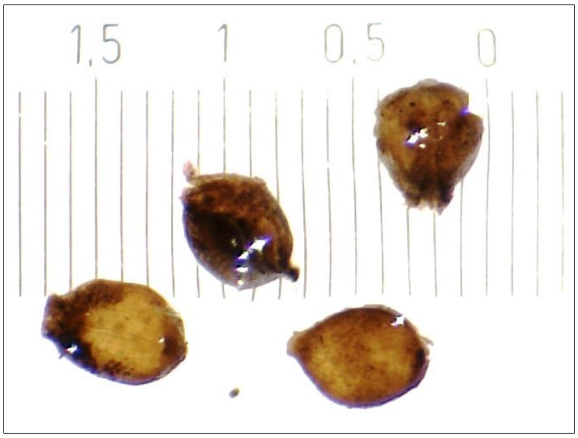
Chara sp. (oospores)



Cladium mariscus subsp. *jamaicense* (seed)

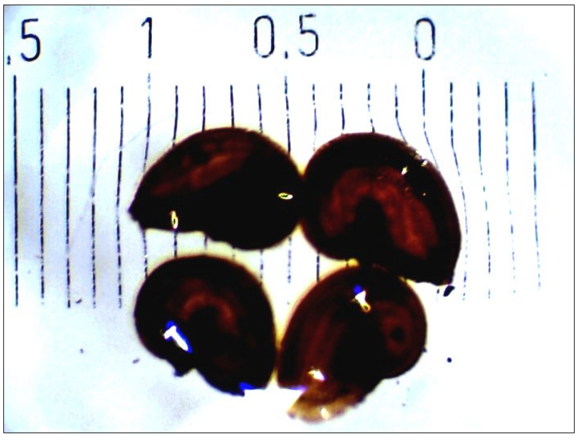
Cladium mariscus subsp. *jamaicense* (seed)

Cyperus sp. (fruits)



Cyperus sp. (fruits)

Pictur of fossils with focus on the scale (in mm)

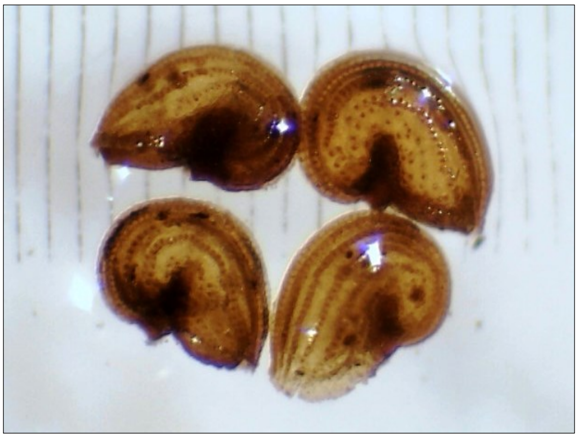


Dissotis canescens (seeds)

Eleocharis acutangula (fruit)

Eleocharis dulcis (fruit)

Picture of fossils with focus on colour and surface



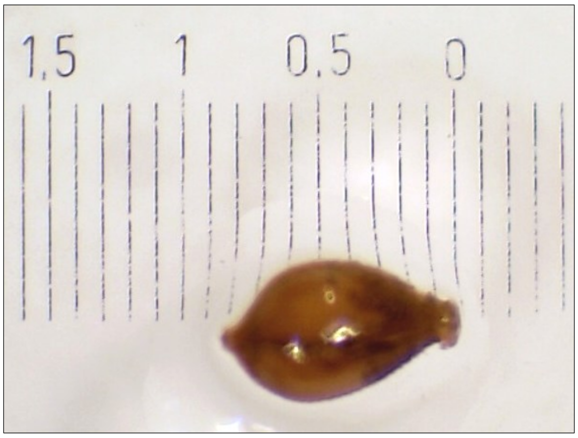
Dissotis canescens (seeds)

Eleocharis acutangula (fruit)

Eleocharis dulcis (fruits)

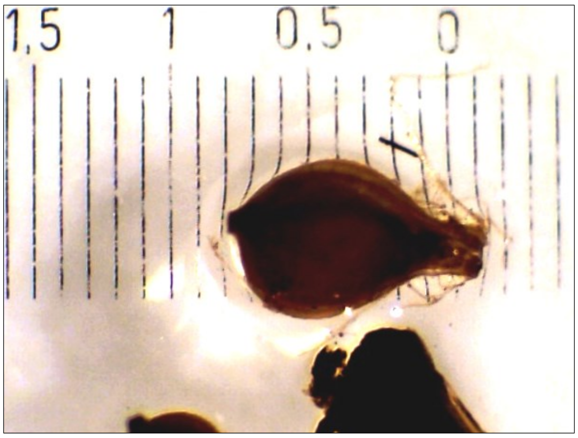
Picture of fossils with focus on the scale (in mm)

Picture of fossils with focus on colour and surface

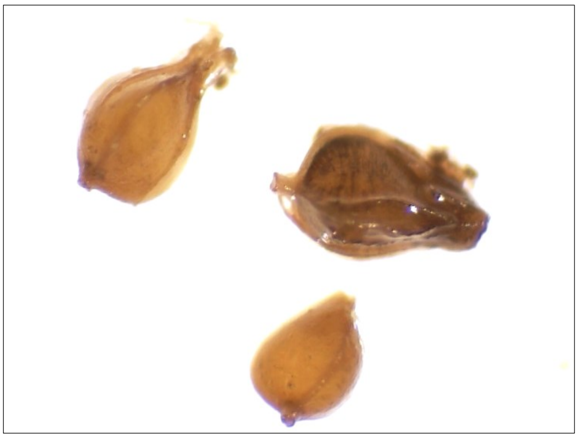


Fuirena obcordata (fruit)

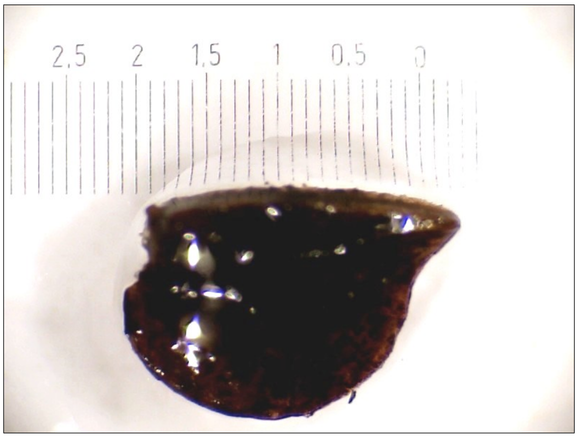
Fuirena obcordata (fruit)



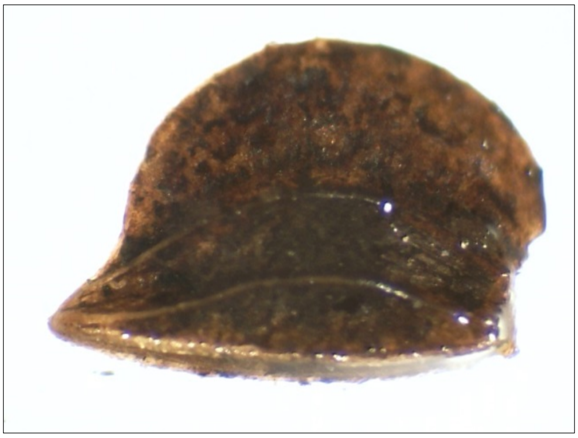
Fuirena umbellata (fruits)



Fuirena umbellata (fruits)



Hydrocotyle bonariensis (fruit)



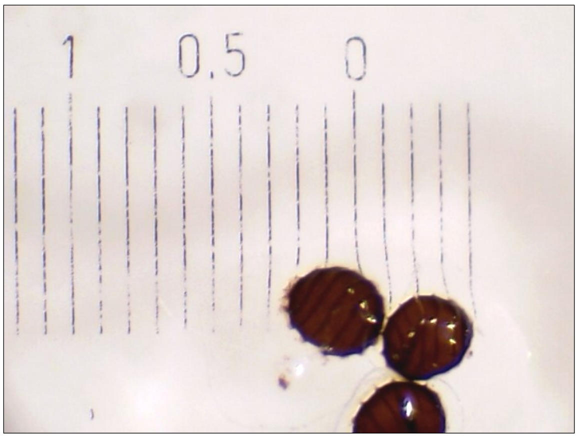
Hydrocotyle bonariensis (fruit)

Picture of fossils with focus on the scale (in mm)

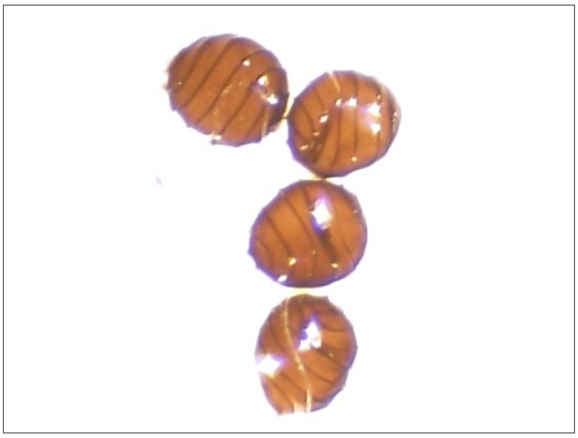
Picture of fossils with focus on colour and surface

Najas sp. (seed)

Najas sp. (seed)



Nitella sp. (oospores)



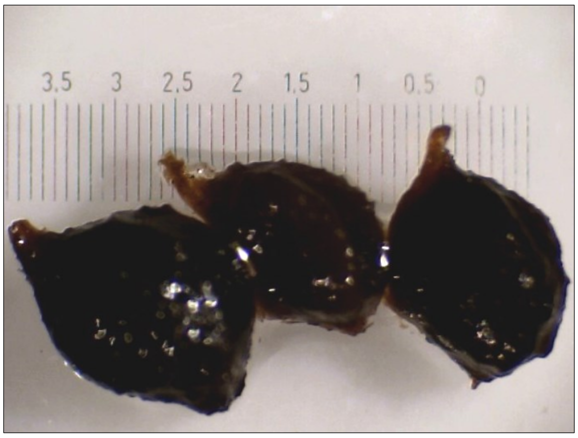
Nitella sp. (oospores)

Nymphaea sp.(seed)

Nymphaea sp. (seeds)

Picture of fossils with focus on the scale (in mm)

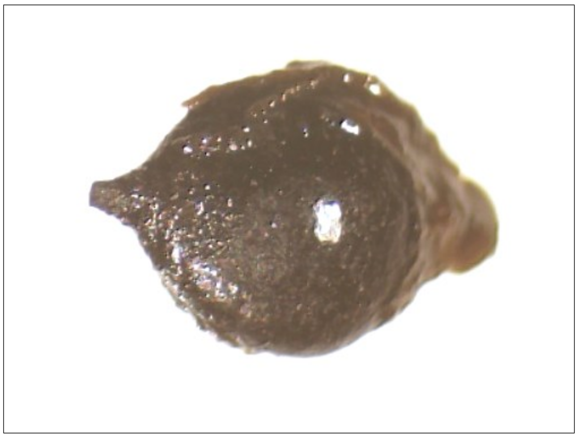
Persicaria amphibia (fruit)



Potamogeton sp. (endocarps)

Pycreus nitidus (fruits)

Picture of fossils with focus on colour and surface



Persicaria amphibia (fruit)

Potamogeton sp. (endocarps)

Pycreus nitidus (fruits)

Picture of fossils with focus on the scale (in mm)

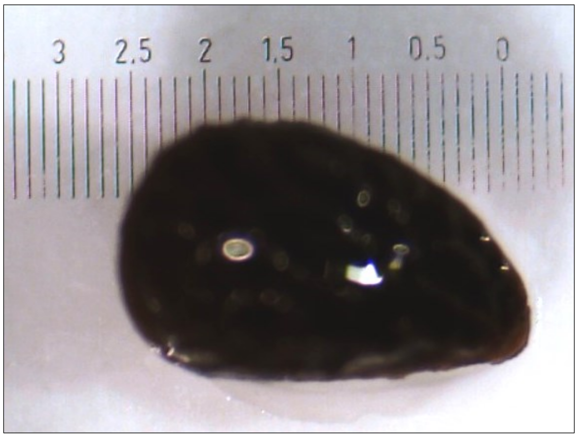
Picture of fossils with focus on colour and surface

Pycreus polystachyos (fruits)

Pycreus polystachyos (fruits)

Rhynchospora holoschoenoides (fruits)

Rhynchospora holoschoenoides (fruits)



Rubus sp. (seed)

Rubus sp. (seed)

Picture of fossils with focus on the scale (in mm)

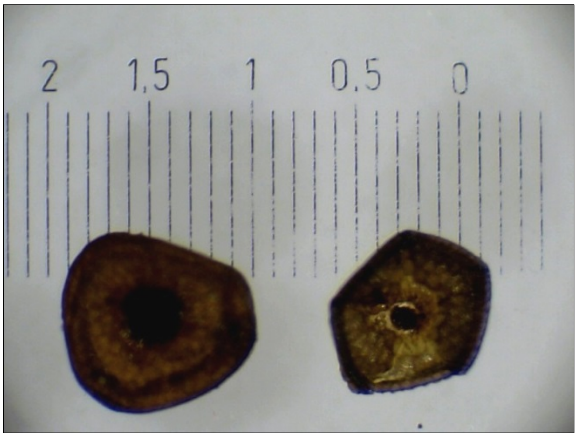
Picture of fossils with focus on colour and surface

Schoenoplectus corymbosus (fruit)

Schoenoplectus corymbosus (fruit)

Typha capensis (seeds)

Typha capensis (seeds)



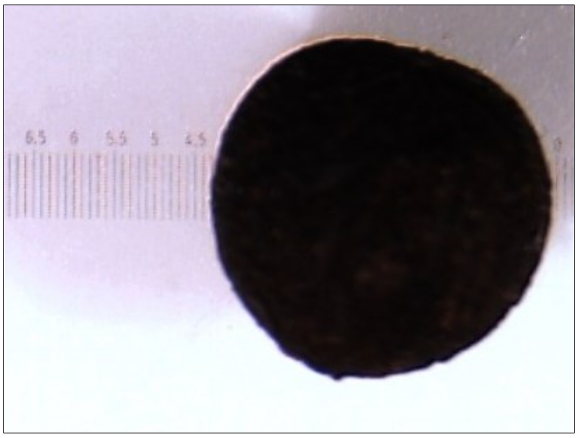
Utricularia sp. (seeds)

Utricularia sp. (seeds)

List of unidentified macrofossils

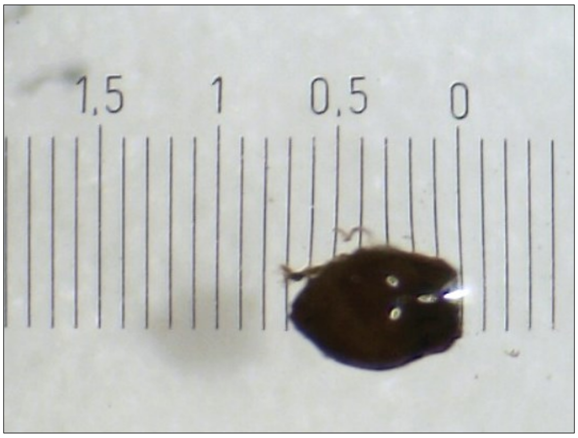
Picture of fossils with focus on the scale (in mm)

Picture of fossils with focus on colour and surface



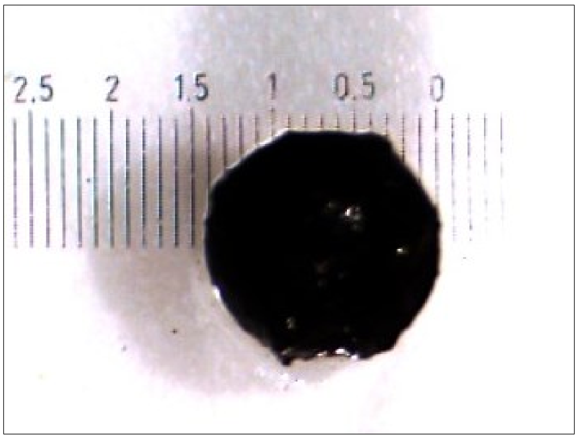
Unkown 3, site UVB (probably seed of tree or shrub)

Unkown 3, site UVB (probably seed of tree or shrub)



Unknown 1, site ID (fruit)

Unknown 1, site ID (fruit)



Unknown 5, site ID (probably fruit)

Unknown 5, site ID (probably fruit)

Appendix 3

Catalogue of South African Peatland Substrates – A guide for field recognition

Available under:
https://www.researchgate.net/publication/321717132_Catalogue_of_South_African_Peatland_Substrates_-_A_guide_for_field_recognition

Catalogue of South African Peatland Substrates

A guide for field recognition

Formation
Morphological Description
Typical Soil Qualities

Echanger pour changer
Wandel durch Austausch
DAAD
ARC • LNR
Excellence in Research and Development
WETREST
Centre for Wetland Research and Training
UNIVERSITY OF ZULULAND
RESTRUCTURED FOR RELEVANCE
UNIVERSITY OF THE FREE STATE
UNIVERSITEIT VAN DIE VRYSTAAT
YUNIVESITHI YA FREISTATA
UFS
UV
HNE Eberswalde
Eberswalde University for Sustainable Development
University of Applied Sciences
HUMBOLDT-UNIVERSITÄT ZU BERLIN

Catalogue of South African Peatland Substrates – A guide for field recognition

Preface

The peatland substrate portraits are a side product of the DAAD (German Academic Exchange Service) -funded research initiative AllWet-RES (Alliance for Wetlands – Research and Restoration) between the University of the Free State, the University of Zululand, the Technische Universität München and the Humboldt-Universität zu Berlin. It was further supported by the Agricultural Research Council (ARC) and The Centre for Wetland Research and Training (WETREST). The main aim of AllWet-RES was the investigation of threads to peatland soils through cultivation practices and afforestation. During this research, data on soil qualities was acquired, for substrates of peatlands in the region of KwaNgwanase (Manguzi) in northern KwaZulu-Natal. They might not be representative for peatland substrates in other parts of South Africa with a different geological background. Other peatland substrates, which are not covered by this compilation, might also be found.

The development of the *Catalogue of South African Peatland Substrates* is based on the concept of mire substrate portraits, elaborated by Meier-Uhlherr et al. (2011) of the Eberswalde University for Sustainable Development. In an ongoing participative investigation project, these researchers gather information on peatland substrates worldwide in order to create a global catalogue of peatland substrate portraits (Luthardt et al. 2016).

Author: Marvin Gabriel
from
Humboldt-Universität zu Berlin
Division of Soil Science and Site Science
Albrecht-Thaer Weg 2
14195 Berlin Dahlem
Germany
Email: Marvin.Gabriel@posteo.de

In cooperation with

University of the Free State
Centre of Environmental Management
PO Box 339
Bloemfontein
South Africa

Eberswalde University for Sustainable Development
Department of Landscape Management and Nature Conservation
Schicklerstraße 5
16225 Eberswalde
Germany

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Contents

Page

Introduction

This is a compilation of portraits of South African peatland substrates. It will serve scientists, as well as consultants and environmental institutions. With images and descriptions it intends to give a brief and compact overview and to facilitate the field recognition. At present neither the South African Soil Classification system “The Blue Book” (Soil Classification Working Group, 1991), nor the internationally used Guidelines for Soil Description (FAO, 2006), provide a scheme for a detailed differentiation of substrates from peatlands. Based on the system of the German Soil Mapping Directive “KA5” (Ad-hoc-AG Boden, 2005) in this document peatland substrates are categorised according to *Peatland Substrate Groups*, *Substrate Types* and *Substrate Subtypes*, the latter defined by the main peat forming plant species (see page 6).

In this way, the Catalogue of South African Peatland Substrates provides a basis for a more detailed peatland description. It can be used for the easy delineation of peatlands and investigation of peatland stratigraphies, by analysing and comparing the substrates’ colour, morphology and macrofossils. The knowledge of peatland substrates can also facilitate decision making when it comes to the designation of areas as conservation priorities or target areas for restoration.

In addition, it provides basic information on the following soil qualities: Carbon content, carbon to nitrogen ratio, pH-value, bulk density, total porosity and hydraulic conductivity. Based on this data, the portraits can be used by researchers and consultants during ground truth campaigns for first estimations of landscape ecological and hydrological functions, like water storage, carbon storage and water flow regulation.

Last but not least, the differentiation of four horizons of amorphous peat according to the degradation intensity allows the evaluation and monitoring of peatland degradation.

The substrate types fluvial loam and organic rich colluvial deposits are not included in this compilation of substrate portraits.

More information on peatland substrates in South African can be found in the following scientific publications: Smuts (1997), Grundling et al. (1998), Faul et al. (2016), Gabriel et al. (2017a) and Gabriel et al. (2017b).

Methodology

The methods used for the determination of the substrate properties are the following:

Field methods

Degree of peat decomposition – Squeezing test according to von Post (1922) (See page 6)

pH-value – Determination with field electrode (Eutech CyberScan PC 650)

Laboratory methods

Content of carbon – Determination with elemental analyser: TruSpec CHN-Determinator. Conversion factor organic carbon to organic matter = 1.88 as suggested by Farmer et al. (2014) for tropical peat (total carbon equalled organic carbon as none of the substrates contained carbonates)

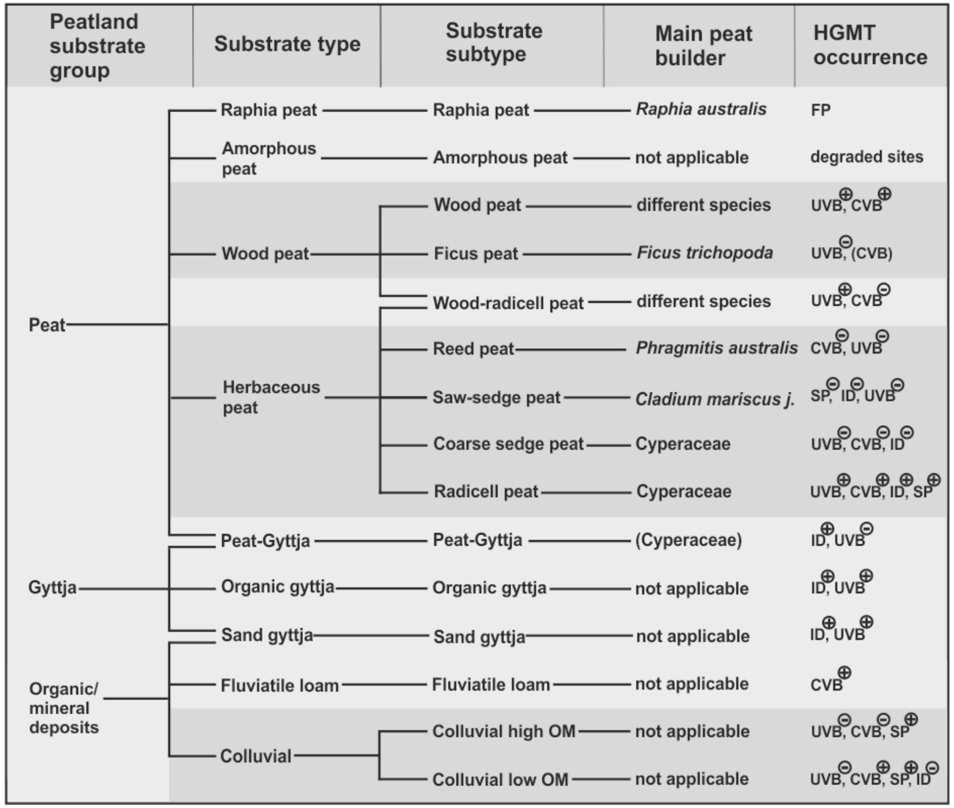
Content total nitrogen - Determination with elemental analyser: TruSpec CHN-Determinator

Bulk density – Determination with volumetric sample rings (100 cm³) according to DIN EN 15934: 2012-11

Total porosity – Determination with volumetric sample rings (100 cm³) by weight loss of water-saturated soil after drying 48 hours at 105°C

Saturated hydraulic conductivity – Falling head method according to Jury et al. (1991)

Characterisation of peatland substrates



Substrate reference scheme suggested by Gabriel et al. (2017b) HGMT = Hydrogeomorphic wetland type according to Ollis et al. (2013); UVC = Unchannelled valley-bottom; CVB = Channelled valley-bottom; ID = Interdune depression; SP = Seep; FP = Flood Plain; ⊕ = common occurrence; ⊖ = rare occurrence.

Degree of peat decomposition

Degree of de-composition	State of squeezed liquid	Proportion of peat extruded	Nature of plant residues	Description
H1	Clear, colourless	None	Plant structure unaltered, fibrous, elastic	Undecomposed
H2	Almost clear, yellow-brown	None	Plant structure distinct, almost unaltered	Almost undecomposed
H3	Slightly turbid, brown	None	Plant structures distinct, most remains easily identifiable	Very weakly decomposed
H4	Strongly turbid, brown	None	Plant structure distinct, most remains identifiable	Weakly decomposed
H5	Strongly turbid, contains a little peat in suspension	Very little	Plant structure clear but indistinct and difficult to identify	Moderately decomposed
H6	Mud, much peat in suspension	One-third	Plant structure indistinct but clearer in residue, most remains undefinable	Well decomposed
H7	Strongly muddy	Half	Plant structure indistinct	Strongly decomposed
H8	Thick mud, little free water	Two-thirds	Plant structure very indistinct – only resistant material such as roots	Very strongly decomposed
H9	No free water	Almost all	Plant structure almost unrecognisable	Almost completely decomposed
H10	No free water	All	Plant structure not recognisable, amorphous	Completely decomposed

Determination of the degree of decomposition after von Post (1922) Test: Take an egg-sized quantity of peat soil and squeeze it over back of your other hand. Investigate water and peat material which extrudes the hand and the residues which remain in the squeezing hand. Degree of decomposition (degree of humification is determined according to the instructions of the table.

Radicell peat (Sedge peat)

Peatland substrate group: **Peat**
Substrate type: **Herbaceous peat**
Substrate subtype: **Radicell peat**

Plants which form the peat:
Cyperaceae, e.g. *Pycreus polystachos, Cyperus sensilis, Cyperus prolifer, Pycreus nitidus, Rhynchospora holoschoenoides*

Typical hydrogeomorphic wetland types:
Interdune depression, Seep, Unchannelled valley-bottom, Channelled valley-bottom

Plant community:
Reed-sedge mire

Typical substrate properties (standard deviation in brackets, sample size in square brackets)

Degree of peat decomposition*	**H4-H7 (typical)**
Content of organic matter	**75% (13.7%) [18]**
C/N ratio	**23.5 (4,5) [15]**
Trophic group**	**mesotrophic**
pH-Value	**4.5 (0,4) [12]**
pH group**	**acid**
Bulk density	**0.12 g/cm^3 (0.05 g/cm^3) [16]**
Total porosity	**94.3% (2.3%) [11]**
Saturated hydraulic conductivity	**710 cm/day (1460 cm/day) [29]**

*according to von Post (1922)
**according to Succow & Joosten (2001)


Photo: F. Faul

Example of peat forming sedge (*Pycreus polystachyos*)

Radicell peat (red bar = 10 cm)

Morphological description

Colour: Usually brown colour; yellow to light brown shades are common as well. The colour darkens when freshly exposed to aerobic conditions.

Morphology: Radicell peat consists mainly of the radicells of sedges (Cyperaceae), which build a dense net or felt. It can be torn apart with the fingers, showing a little resistance to strain. The radicells which build the bulk of the peat are small (<1mm), even though stem bases and larger rootlets occur as well. The radicells are densely interwoven. Looking with a microscope and extra light, the colour of the radicells will be noticed as yellow-white shades with different degrees of transparency.

Possible intermixtures: Radicells from plants other than sedges are very likely, as many species can co-occur with them, e.g. *Typha capensis, Phragmitis australis, Dissotis canescens, Persicaria amphibia, Thelypteris interrupta.* Amorphous decomposed peat and organic gyttja might also be present in the matrix, as brown and muddy parts. Sand is a common intermixture in peatlands of the Maputaland Coastal Plain and is usually found in increasing amounts from the central peatland towards the fringe.

Dense root system of *Pycreus polystachyos*

Forming environment

Radicell peat is the most frequently encountered peat type. It forms the main substrate in mature interdune depression peatlands and can also be encountered in unchannelled valley-bottoms, channelled valley-bottoms and seeps. The radicell peat forming sedge communities are the typical vegetation type after completed terrestrialisation processes. It unchannelled valley-bottoms it was followed in the natural succession by peat swamp forest.

Further it may form in peatlands in unchannelled valley-bottoms and channelled valley-bottoms, which have been drained and cleared from peat swamp forest vegetation. Reed-sedge vegetation might appear in succession, when the fields are abandoned after cultivation. Eventually, after some decades, peat swamp forest will succeed and replace the reed-sedge vegetation again.

Photo: N. Guerrero-Moreno

Sedge community in peatland

Reed-sedge vegetation in succession of cleared peat swamp forest

Wood peat

Peatland substrate group: Peat
Substrate type: Wood peat
Substrate subtype: -

Plants which form the peat:
Ficus trichopoda, Voacanga thouarsii, Syzygium cordatum

Typical hydrogeomorphic wetland types:
Unchannelled valley- bottom
Channelled valley-bottom

Plant community:
Peat swamp forest

Typical substrate properties (standard deviation in brackets, sample size in square brackets)

Degree of peat decomposition*	**H4-H6 (typical)**
Content of organic matter	81.2% (11.2) [12]
C/N ratio	24.1 (5.8) [8]
Trophic group**	mesotrophic
pH-Value	4.5 (0.4) [7]
pH group**	acid
Bulk density	0.09 g/cm^3 (0.02 g/cm^3) [15]
Total porosity	96.3% (1.8%) [7]
Saturated hydraulic conductivity	**2038 cm/day (2811 cm/day) [15]**

*according to von Post (1922)
**according to Succow & Joosten (2001)

Example for wood peat forming plant: *Ficus trichopoda* (with typical aerial roots)

Wood peat

Morphological description

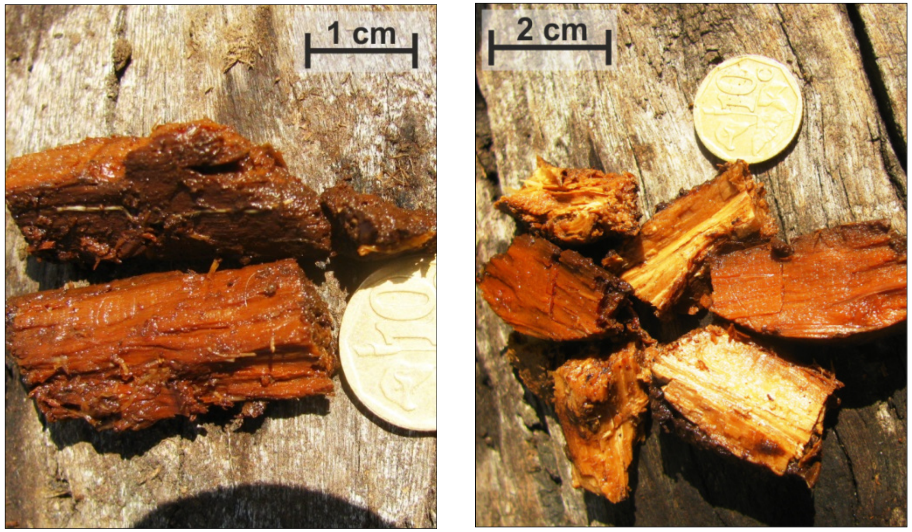
Morphology and Colour: Wood peat consists mostly of decomposing wood (from roots and/or stems and branches) with a still-recognizable shape. With a microscope one can also see small brownish radicells which are stiffer than herbal radicells and also originate from the trees. The overall structure is spongy. The typical degree of decomposition is between the von Post values H4-H6. In high decomposition degrees (H8-10) the consistency is soft and crumbly, with a consistency reminiscent of expanded polystyrene foam. Peat residues of ***Ficus trichopoda*** wood have a red colour and a very distinct fibrous appearance. In medium decomposed wood (H4-H6) the fibres are very well distinguishable. They are singularly with a roundish or flattened cross section and about 1 mm broad. Wood can be encountered with bark. Peat residues of ***Syzygium cordatum*** wood also have a red colour like *Ficus trichopoda* wood, but the fibres appear less singular and rather irregularly arranged. Soft *Syzygium cordatum* wood typically breaks with sharp edges, and pieces found in the peat have often a slightly rectangular appearance. Wood can be encountered with bark. Peat residues of ***Voacanga thouarsii*** have a yellowish or yellow-brown colour. The fibres are very fine and not very prominent. In better preserved samples fine medullary rays can be visible. Peat residues of Voacanga thouarsii are not encountered with bark.

Wood: (*Ficus trichopoda*) red-brown

Possible intermixtures: Wood residues might also come from other less frequent peat swamp forest trees like *Bridelia micrantha*, and *Syzygium guineense*. Radicells from herbal plants in the understory. *Scleria angusta, Cyperus textilis* are frequently encountered.

Forming environment

Wood type occurs typically in channelled valley-bottom peatlands or unchannelled valley-bottom peatlands, where it is formed by peat swamp forest vegetation. More precisely, it forms out of the decomposing wood of dead trees. This may come from roots, but also trunks and branches of trees. A certain indicator that above-ground parts of trees formed a peat layer is the occurrence of semi-decomposed leaves within the peat, as well as macrofossils like seeds from peat swamp forest species.



Wood: left *(Syzygium cordatum) red;* right *(Voacanga thouarsii) yellow*

Peat swamp forest in channelled valley-bottom

Wood-radicell peat

Peatland substrate group: **Peat**
Substrate type: **Wood- & herbaceous peat**
Substrate subtype: **Wood-radicell peat**

Plants which form the peat:
Cyperaceae, *Voacanga thouarsii, Syzygium cordatum, Ficus trichopoda*

Typical hydrogeomorphic wetland types:
Unchannelled valley- bottom
Channelled valley-bottom

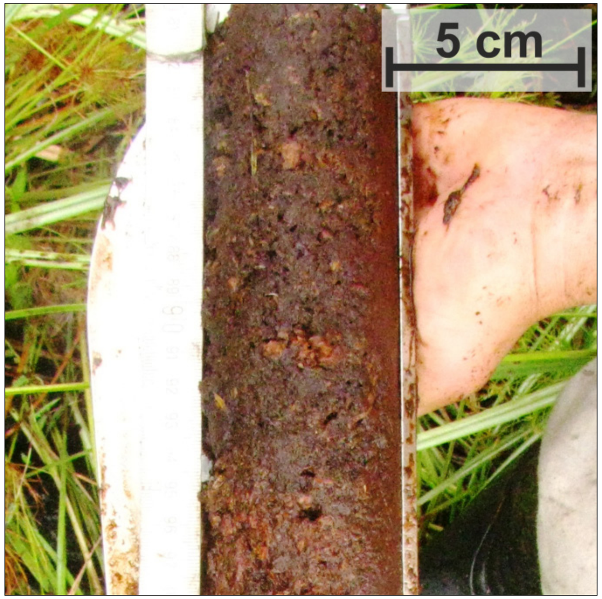
Plant community:
Reed-sedge vegetation
Peat swamp forest vegetation

Typical substrate properties (standard deviation in brackets, sample size in square brackets)

Degree of peat decomposition*	H5-H6 (typical)
Content of organic matter	81.2% (11.2) [12]
C/N ratio	24.1 (5.8) [8]
Trophic group**	mesotrophic
pH-Value	4.5 (0.4) [7]
pH group**	acid
Bulk density	0.09 g/cm³ (0.02 g/cm³) [15]
Total porosity	96.3% (1.8%) [7]
Saturated hydraulic conductivity	813 cm/day (926 cm/day) [15]

*according to von Post (1922)
**according to Succow & Joosten (2001)

Root system of *Cyperus sphaerospermus*



Wood-radicell peat in peat core

Morphological description

Colour: Wood-radicell peat usually shows a mix of colours, typically including yellow and brown shades. Depending on the wood type, red components may also be found.

Morphology: Wood-radicell peat consists of decomposing wood and radicells. Wood residues in the peat mostly originate from *Ficus trichopoda, Syzygium cordatum* and *Voacanga thouarsii*, which are described in the portrait of wood peat. Radicells are mostly originating from sedge vegetation (Cyperaceae) and are small (<1mm), even though stem bases and larger rootlets occur as well. Looking with a microscope and extra light, the colour of the sedge radicells will be noticed as yellow-white shades with different degrees of transparency. Radicells which originate from trees are brownish and stiffer than herbal radicells.

Wood-radicell peat with wood of *V. thouarsii*

Forming environment

Two different possibilities exist for the formation of wood-radicell peat.

1. A sedge mire (Cyperaceae vegetation) is followed in the peatland's genesis by a peat swamp forest and tree roots from above penetrate the sedge peat underneath.
2. A peat swamp forest which accumulates wood peat is cleared (e.g. for cultivation) and when abandoned again the succession vegetation is formed of Cyperaceae communities.

In both scenarios, the resulting substrate is a mixture of residual wood with radicells and stem bases from sedges. It can be encountered in various degrees of decomposition from H3 to H9. High degrees are especially common in scenario 2 when drainage was applied in addition to the wood clearing and the initial wood peat became highly decomposed.

Spread wood-radicell peat (yellow wood: *Voacanga thouarsii*)

Succession vegetation community in unchannelled valley-bottom with **reed-sedge vegetation:** *Typha capesis* and Cyperaceae; and **trees:** *Syzygium cordatum* and *Voacanga thouarsii*

Coarse sedge peat

Peatland substrate group: Peat
Substrate type: Herbaceous peat
Substrate subtype: Coarse sedge peat

Plants which form the peat:
Stout Cyperaceae species, e.g. *Cyperus dives*, *Cyperus prolifer* and *Cladium mariscus jamaicense*

Typical hydrogeomorphic wetland types:
Unchannelled valley-bottom, Channelled valley-bottom, Interdune depression

Plant community:
Sedge mire

Typical substrate properties (standard deviation in brackets, sample size in square brackets)

Degree of peat decomposition*	**H3-H7 (typical)**
Content of organic matter	**93 % (2.6%) [4]**
C/N ratio	**29 (4.5) [2]**
Trophic group**	**mesotrophic**
pH-Value	**4.8 (0.1) [2]**
pH group**	**acid**
Bulk density	**0.1 g/cm³ (0.01 g/cm³) [20]**
Total porosity	**93.4 % (2%) [12]**
Saturated hydraulic conductivity	**159 cm/day (91 cm/day) [9]**

*according to von Post (1922)
**according to Succow & Joosten (2001)

Example for coarse sedge peat forming plant: *Cyperus prolifer*

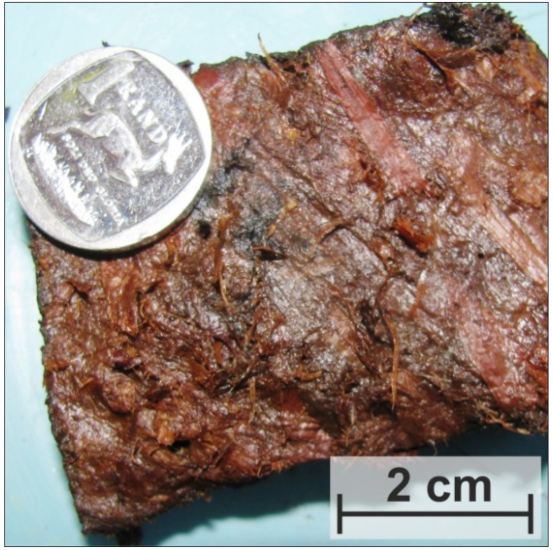
Coarse sedge peat

Morphological description

Colour: Coarse sedge peat generally has a brownish colour. It can have yellowish to light-brown shades if well preserved. Colour darkens after a few minutes of exposure to aerobic conditions.

Morphology: Coarse sedge peat consists of stem bases of Cyperaceae and their roots. The main components of the substrate are stem bases. They usually appear in flattened cylindrical segments of 0,5-2 cm in diameter and 1-5 cm in length. Fine rootlets with 1 mm or less are also present. Also the typical stem bases of *Cladium mariscus jamaicense* may be found in coarse sedge peat, which in some cases form their own peat type (saw-sedge peat). If mainly consisting of well preserved stem bases and rootlets, the degree of decomposition can be as low as H3. The von Post test yields higher results if the substrate contains gyttja.

Possible intermixtures: Organic gyttja as an intermixture is frequently encountered. In peatlands of the Maputaland Coastal Plain sand is a common intermixture, which is found in increasing amounts from the central part of the peatland towards the fringe.



Compressed coarse sedge peat

Forming environment

Coarse sedge peat is a rather rare substrate which forms in very wet ecosystems. It forms out of sedges which grow in inundated areas. This can be the case in terrestrialising unchannelled valley-bottoms and interdune depressions, after a deeper limnic system became shallower when filled with gyttja or the water table dropped due to drier climatic conditions. Therefore, within the stratigraphy of a peatland, it is usually found in transition between organic gyttja and radicell peat.
It is probably indicative of times in which seasonal water table fluctuations are less pronounced. It was also found in the stratigraphies of channelled valley-bottom peatlands (which have generally less pronounced water table fluctuations). Whether this occurrence is natural or only in succession after wood-cutting needs further investigation.

Photo: C. Rodríguez Martinez

Sedge community growing in an interdune depression peatland

Mixed tall sedge communities in an interdune depression

Saw-sedge peat (Cladium peat)

Peatland substrate group: Peat
Substrate type: Herbaceous peat
Substrate subtype: Saw-sedge peat

Plants which form the peat:
Cladium mariscus jamaicense

Typical hydrogeomorphic wetland types:
Interdune depression
Unchannelled valley-bottom
Seep

Plant community:
Reed-sedge mire

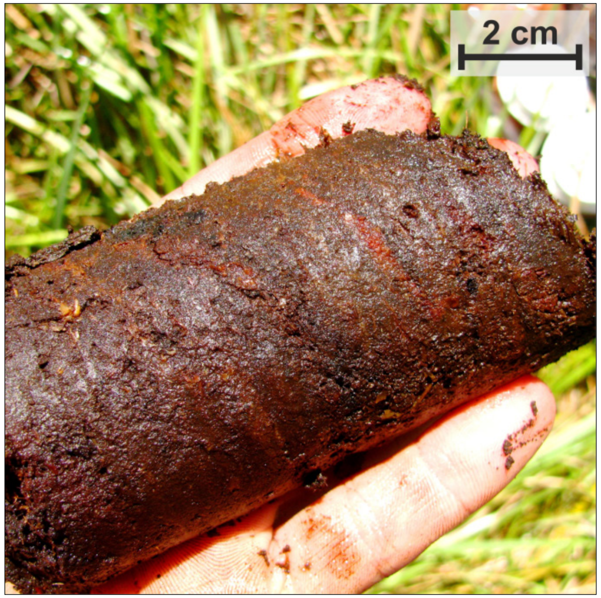
Typical substrate properties standard deviation in brackets, sample size in square brackets)

Degree of peat decomposition*	**H4-H7 (typical)**
Content of organic matter	**92.7% (1.1%) [4]**
C/N ratio	**41.1 (-) [1]**
Trophic group**	**oligotrophic**
pH-Value	**4.9 (-) [1]**
pH group**	**subneutral**
Bulk density	**0.1 g/cm³ (0.01 g/cm³) [11]**
Total porosity	**92% (3.1%) [6]**
Saturated hydraulic conductivity	**165 cm/day (102 cm/day) [4]**

*according to von Post (1922)
**according to Succow & Joosten (2001)


Photo: F. Faul

Inflorescence of *Cladium mariscus jamaicense*



Saw-sedge peat in sample peat core

Morphological description

Colour: The peat consists of reddish fibrous stem bases of *Cladium mariscus jamaicense* within a brownish matrix. Taken out of anaerobic conditions, the colour of the stem bases turns to brown in 1-2 minutes.
Morphology: Peat-forming parts of the plant are the stem bases and probably also radicells. One typically finds the stem bases as soft and fibrous pieces of 2-4 cm length and about 1 cm width. They resemble decomposed wood. Saw-sedge peat is usually encountered in a medium degree of decomposition from H4-H7, whereas some of the squeezed material is certainly gyttja and not decomposed peat.
Possible intermixtures: Rhizomes of *Phragmitis australis* and *Typha capensis* may be encountered. Also radicells from other Cyperaceae species, e.g. *Eleocharis dulcis* .

Macrofossil: stem base of *C. mariscus j.*

Forming environment

Saw-sedge peat is a rather rare substrate which forms in very wet ecosystems. It accumulates in shallow inundated areas, in similar conditions to coarse sedge peat, out of the stem bases of *Cladium mariscus jamaicense*. This can be the case in terrestrialising unchannelled valley-bottoms and interdune depressions, after a deeper limnic system became shallower when filled with gyttja or the water table dropped due to drier climate. Therefore, within the stratigraphy of a peatland, it is usually found in transition between organic gyttja and radicell peat.

It was also found in the lowest part of a seep peatland, in transition to a valley bottom, probably indicating formerly higher water tables.

Homogenous stand of *Cladium mariscus jamaicense*

***Cladium mariscus jamaicense* in interdune depression peatland**

Ficus peat

Peatland substrate group: Peat
Substrate type: Wood peat
Substrate subtype: Ficus peat

Plants which form the peat:
Ficus trichopoda

Typical hydrogeomorphic wetland types:
Unchannelled valley- bottom
Channelled valley-bottom

Plant community:
Peat swamp forest

Typical substrate properties (standard deviation in brackets, sample size in square brackets)

Von Post degree of decomposition*	**H3-H6 (typical)**
Content of organic matter	**93.6% (5%) [3]**
C/N ratio	**68 (-) [1]**
Trophic group	**oligotroph**
pH-Value	4.7 (-) [1]
pH group**	acid
Bulk density	**0.1 g /cm³ (0.01g/cm³) [3]**
Total porosity	94.2 % (0.4%) [2]
Saturated hydraulic conductivity	**704 cm/day (288 cm/day) [2]**

*according to von Post (1922)
**according to Succow & Joosten (2001)

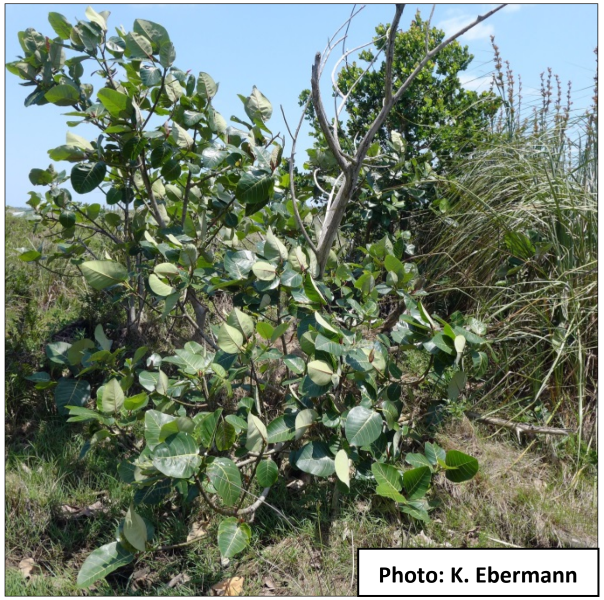


Photo: K. Ebermann

Small *Ficus trichopoda* tree

Ficus peat

Morphological description

Colour: The colour varies from light red, through deep red to light red-brown and dark red-brown.
Morphology: Ficus peat consists mostly of decomposing wood which still has a recognizable shape. When present, the fraction of amorphous matter is muddy and brownish. Leaves may be found as well. The overall structure is spongy. The typical degree of decomposition is between the von Post values H3-H6. In high decomposition degrees (H8-10) soft and crumbly, with a consistency that reminds of polystyrene. Single pieces of *Ficus trichopoda* wood have a very distinct fibrous appearance. In medium decomposed wood (H4-H6) the fibres are very well distinguishable. They are singular with a roundish or flattened cross section and about 1 mm broad. In low decomposed wood (<H4) the structure is more compact and the fibres are less prominent. A longitudinally-opened, medium decomposed twig may be reminiscent of an uncooked packet of spaghetti. In a medium degree of decomposition the wood pieces lose their coherence and the fibres become more flexible and formable. However, beyond a slight strain they tear.
Possible intermixtures: Wood peat from *Voacanga thouarsii* and *Syzygium cordatum,* radicells of *Cyperus textilis.* Within peat layers of peat swamp forests, water inclusions (hollow parts filled with water) are common.

Semi-decomposed *Ficus trichopoda* wood

Forming environment

Ficus peat forms out of homogenous stands of *Ficus trichopoda* trees in peat swamp forests. Peat swamp forests form in South Africa mainly in the hydrogeomorphic wetland types channelled valley-bottom and unchannelled valley-bottom.

Ficus trichopoda also grows in a vegetation community with the sedge *Cyperus textilis*, as a result of which radicells of *Cyperus textilis* may also be found in ficus peat.


Photo: M. Riedel

Ficus trichopoda* growing with the sedge *Cyperus textilis


Photo: T. Thrum

***Ficus trichopoda* dominated peat swamp forest in a CVB**

Raphia peat

Peatland substrate group: <u>Peat</u>
Substrate type: <u>Raphia peat</u>
Substrate subtype: -

Plants which form the peat:
Raphia australis

Typical hydrogeomorphic wetland types:
Flood plain
(maybe also valley-bottom types)

Plant community:
Raphia australis swamp forest

Typical substrate properties (standard deviation in brackets, sample size in square brackets)	
Degree of peat decomposition*	**H4-H7 (typical)**
Content of organic matter	**61.9% (6%) [4]**
C/N ratio	**22.1 (3.4) [4]**
Trophic group**	**mesotrophic**
pH-Value	**6.1 (0.3) [4]**
pH group**	**subneutral**
Bulk density	**0.18 g/cm³ (0.05 g/cm³) [4]**
Total porosity	**95.2% (2.1%) [3]**
Saturated hydraulic conductivity	**614 cm/day (1088 cm/day) [9]**

*according to von Post (1922)
**according to Succow & Joosten (2001)


Photo: N. Guerrero Moreno

***Raphia australis* palm**

Photo: F. Faul

Shallow peat profile (30 cm) of *Raphia* peat

Morphological description

Colour: Brownish (amorphous matrix) with radicells of a white-yellow colour.
Morphology: Dense felt of radicells (ca. 1 mm) with bigger roots (1-8 mm) and amorphous material. Radicells of the tangle of roots are hollow and slightly broader than sedge radicells. In the top 5 cm of the soil profile small woody plates, probably the outer shell of the midribs from the large *Raphia australis* leaves, are found, but not deeper.
Possible intermixtures: Sand and other fluvial sediments might be encountered, when raphia peat developed on flood plains.

Radicells and pneumathodes of *R. australis*

Forming environment

Raphia australis grows on temporarily inundated areas around the Kosi Lake System. The root system (left picture) consists of thick (mostly vertical) roots (ca. 8 mm diameter) which are soft and light in colour. Smaller roots (1-2 mm diameter) branch off from these at irregular distances of 1-5 cm. Radicells (ca. 1 mm) branch off from these smaller roots and produce a dense felt in the soil.

Like other *Raphia* species its roots are pneumathodes, e.g. they are able to conduct oxygen in water saturated soil, what allows them to grow in damp places. They produce an aerobic environment in the soil around themselves which allows organisms to decompose organic matter. It is probable that the oxygen conduction into the water-saturated soil stops after the death and the decomposition of a root. Thereafter, the decay of the remaining residues becomes reduced, which allows the accumulation of peat.


Photo: F. Faul

***Raphia australis* forest**

***Raphia australis* forest with remaining midribs of fallen leaves**

Peat-Gyttja

Peatland substrate group: Peat & Gyttja
Substrate type: Peat-Gyttja
Substrate subtype: -

Plants which form the peat:
Aquatic plants (e.g. *Nymphaea* sp.) and semi terrestrial sedges (e.g. *Eleocharis dulcis, Pycreus polystachyos*)

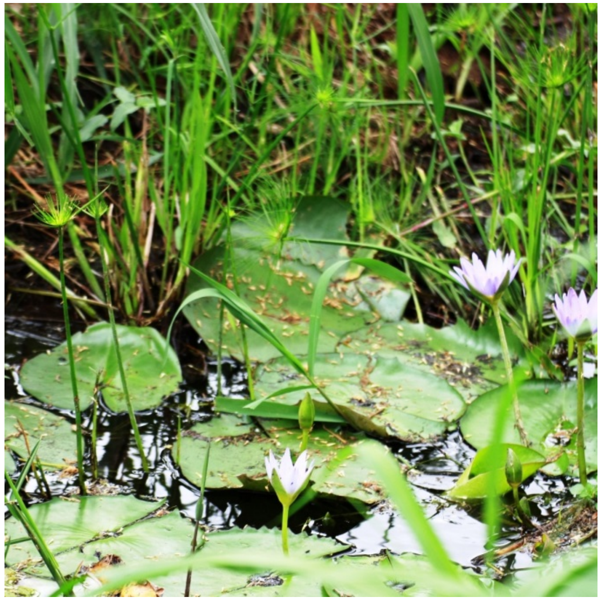
Typical hydrogeomorphic wetland types:
Interdune depression
Unchannelled valley-bottom

Plant community:
Aquatic plants and reed-sedge communities

Typical substrate properties (*standard deviation in brackets, sample size in square brackets*)

Degree of peat decomposition*	**Not applicable (appears like H8-H10)**
Content of organic matter	66.9% (16.6%) [8]
C/N ratio	**26.6 (37) [5]**
Trophic group**	**mesotrophic**
pH-Value	**4.4 (0.3) [5]**
pH group**	**acid**
Bulk density	**0.15 g/cm^3 (0.04 g/cm^3) [11]**
Total porosity	**93.9% (2.9%) [7]**
Saturated hydraulic conductivity	**256 cm/day (213 cm/day) [13]**

*according to von Post (1922)
**according to Succow & Joosten (2001)



Plants forming Peat-Gyttja (*Nymphaea sp., Cyperus prolifer, Eleocharis dulcis*)

Peat-Gyttja in peat corer (red bar = 10 cm)

Morphological description

Colour: Generally brown but can have different shades, like brown with yellow tinge or dark brown. Looking with a microscope and extra light, the colour of the rootlets will be noticed as yellow-white shades with different degrees of transparency.

Morphology: Peat-gyttja is a substrate which consists of organic gyttja and radicell peat in roughly equal quantities. The rootlets which build the bulk of the peat part are usually ≤1mm, even though stem bases and larger rootlets can occur as well. The rootlets are densely interwoven. The gyttja part gives the substrate a jelly-like consistency.

Possible intermixtures: Sand is a common intermixture, which is found in increasing amounts from the central peatland towards the fringe.

Possible intermixture: Root system of *Eleocharis dulcis*

Forming environment

Peat-Gyttja forms where the seasonal water table fluctuations produce inundation for part of the year. This is especially the case in interdune depression peatlands but may also occur in unchannelled valley-bottom peatlands. Moreover, in years with above average precipitation inundations can be prevalent for the whole year and beyond. Throughout dry spells and afterwards, the water table can be below the surface for probably equally long periods. During inundation organic gyttja accumulates, and during non-inundated periods radicell peat accumulates.

Images below show a small pond in the middle of an interdune depression peatland. On the left side during a wet cycle, on the right side during a dry cycle.

Small pond in peatland with *Eleocharis dulcis* (wet season)

Same pond with leaves of *Nymphaea sp*. on dried surface (dry season)

Organic gyttja (Detritus gyttja)

Peatland substrate group: Gyttja
Substrate type: Organic gyttja
Substrate subtype: -

Composition of the substrate

>30 % organic matter
<70% mineral content

Typical hydrogeomorphic wetland types:

Interdune depression
Unchannelled valley- bottom

Plant community:

Aquatic plants and reed-sedge communities at lake/pond fringes

Typical substrate properties standard deviation in brackets, sample size in square brackets)

Degree of peat decomposition*	**Not applicable**
Content of organic matter	**56.1% (17.9%) [15]**
C/N ratio	**27.7 (5.8) [13]**
Trophic group**	**mesotrophic**
pH-Value	**4.9 (0.4) [11]**
pH group**	**subneutral**
Bulk density	**0.19 g/cm³ (0.06 g/cm³) [15]**
Total porosity	**92.1% (3.4%) [2]**
Saturated hydraulic conductivity	**210 cm/day (383 cm/day) [5]**

*according to von Post (1922)

**according to Succow & Joosten (2001)

Possible source for detritus: *Nymphaea sp.,*

Organic gyttja in peat core (red bar = 10 cm)

Morphological description

Colour: The colour is in general brown but it can have different shades, such as brown with a yellow tinge, dark brown, and even almost black organic gyttjas have been encountered.

Morphology: Organic gyttja is an amorphous substrate with a rubberlike consistency. It consists mainly of organic sediments (detritus) and exhibits a certain degree of rebound when pressed gently with the fingers. When torn with the fingers, it is elastic until a certain point but eventually breaks into two distinct pieces. Its appearance might be similar to amorphous peat, but with the difference of the rubberlike consistency and the rebound effect after pressing. To obtain absolute certainty, macro fossils like seeds of water plants must be identified.

Possible intermixtures: In terrestrialisation mires the deeper parts of organic gyttja layers are commonly penetrated by roots with a diameter of 2-5 mm. The upper parts of gyttja layers exhibit increasing quantities of radicells (< 1mm) from Cyperaceae (e.g. *Eleocharis dulcis*). Rhizomes of reeds (e.g. *Phragmitis australis)* and bulrushes (e.g. *Typha capensis)* as well as stem bases of stout Cyperaceae (e.g. *Cladium mariscus jamaicense)* may also be found.

In Maputaland, sand is the main mineral component in organic gyttja and intermixed in low to high quantities. With an organic matter content ≥ 30% (weight of dry matter) it is defined as organic gyttja, below these 30% it is classified as mineral gyttja (in the case of the Maputaland Coastal Plain mostly sand gyttja).

Organic gyttja with some recent roots

Forming environment

Organic gyttja forms on the ground of limnic systems, such as lakes and ponds. It consists of sedimented particles, like decomposed residues of plants and animals, and mineral inputs (e.g. aeolian sand). The plant residues come from aquatic plants as well as from vegetation growing in shallow water at the fringes of lakes and ponds.

With increasing sedimentation the layer of gyttja extends and vegetation starts to colonise the lake/pond. Seasonal water table fluctuations can give advantage to semi-terrestrial plants in the dry seasons. Eventually, the formation of organic gyttja is typically succeeded by the formation of peat-gyttja or radicell peat.

Nymphaea sp. and Eleocharis dulcis in shallow water

Terrestrialising lake with floating mats of Cyperaceae at the fringes

Sand gyttja

Peatland substrate group: Gyttja
Substrate type: Sand gyttja
Substrate subtype: -

Composition of the substrate:
>70% mineral components
<30% organic matter

Typical hydrogeomorphic wetland types:
Interdune Depression
Unchannelled valley-bottom

Typical substrate properties (standard deviation in brackets, sample size in square brackets)

Degree of peat decomposition*	**Not applicable**
Content of organic matter	**14.3% (6.2%) [15]**
C/N ratio	**27.7 (4.7) [11]**
Trophic group**	**mesotrophic**
pH-Value	**4.6 (0.2) [11]**
pH group**	**acid**
Bulk density	**0.63 g/cm^3 (0.35 g/cm^3) [15]**
Total porosity	**68.7% (25.7%) [2]**
Saturated hydraulic conductivity	**168 cm/day (368 cm/day) [7]**

*according to von Post (1922)
**according to Succow & Joosten (2001)


Photo: F. Faul

Wet sand gyttja in a sample core


Photo: F. Faul

Dried sand gyttja (red bar = 10 cm)

Morphological description

Colour: Sand gyttja low in organic matter exhibits grey to light brown colours and sand gyttja with higher organic matter contents deep brown colours.

Morphology: The mineral fraction consists of sand and the organic fraction of detritus. Depending on its organic matter content, which can be up to 30%, its consistency is stiffer (less organic matter) or more elastic (more organic matter).

Possible intermixtures: In already-terrestrialised peatlands, vertical roots (2-5 mm) from the terrestrialisation community commonly penetrate into the sand gyttja underneath. Seeds from vegetation growing at the fringe of lakes are commonly found macrofossils in sand gyttja.

Seeds: *Nymphaea* sp, *Xyris capensis, Cladium mariscus jamaicense, Eleocharis dulcis*

Forming environment

Sand gyttja is the sediment which accumulates on the ground of (shallow) lakes/ponds and is usually the initial substrate formed in terrestrialisation peatlands. These can be found in interdune depressions and unchannelled valley-bottoms. It consists of a mix of sediments made of aeolian sand and semi-decomposed parts of aquatic plants or lake/pond fringe vegetation. In peatland stratigraphies it is commonly succeeded by organic gyttja when the content of organic matter increases continuously from the bottom upwards, eventually reaching the 30% threshold.

Potential ecosystem accumulating sand gyttja

Peatland which initially accumulated sand gyttja (in 80-160 cm)

Amorphous peat

Peatland substrate group: Peat
Substrate type: Amorphous
Substrate subtype: -

Description:

Peat without identifiable plant remains but with a high to maximum degree of decomposition (von Post = H9-H10). Colour: brown to black. Frequently occurs as dry topsoil of drained peatlands. It develops new soil structures according to the intensity of mineralisation. This process is known as the moorsh forming process and four horizons are distinguished (see table to the right).

Formation:

Amorphous peat forms when previously accumulated peat becomes exposed to aerobic conditions and undergoes further decomposition. This happens (and in the past also happened naturally) when the climate becomes drier. (Continued at the right column of the next page)

Drainage ditch exposes ca. 40 cm of peat to aerobic conditions for banana cultivation in channelled valley-bottom

Horizons of the moorsh forming process after Illnicki & Zeitz (2003)

Horizon	Description
1. Grainy moorsh horizon	Topsoil horizon of drained peatlands, mostly with intensive tillage action; very fine granular to dusty structure, hard and dry.
2. Earthification horizon	Topsoil horizon of drained peatlands, due to mineralisation and humification formation of crumby, fine-polyhedral to granular soil structure.
3. Aggregation horizon	Subsoil horizon of drained peatlands. Formation of soil aggregates due to shrinking and swelling; coarse to fine-angular blocky structure, vertical and horizontal shrinkage cracks.
4. Peat shrinkage horizon	Subsoil horizon of drained peatlands, usually directly in transition to non-degraded peat. Oxidation of organic matter and subsidence. Beginning formation of soil structure, vertical cracks.

Dried and burnt Vazi-peatland with deep dessication cracks due to water extraction by surrounding forestry plantations

Grainy moorsh horizon

Earthification horizon

Peat aggregation horizon (between the two grey lines)

Peat shrinkage horizon (red bar = 10 cm)

Moreover, anthropogenic changes in a peatland's hydrology often lead to the drawdown of the water table. This is usually the case when either artificial drainage channels are established for cultivation purposes (left picture previous page) or as a consequence of severely water consuming forestry plantations like *Eucalyptus* or *Pinus* (right picture previous page).

Occurrence:
Amorphous peat can occur in every peatland type. Typically it occurs as the topsoil substrate of peatlands whose hydrology was subject to manmade changes.

The table below shows soil properties for investigated horizons.

Typical substrate properties (standard deviation in brackets, sample size in square brackets)
Shrin. = peat shrinkage horizon; Aggr. = peat aggregation horizon; Eart.= earthification horizon

Property	Eart.	Aggr.	Shrin.
Content of organic matter	62% (13%) [9]	64% (15%) [7]	69 % (12) [6]
C/N ratio Trophic group*	18 (4) [4]	18 (2) [5]	16 (6) [4]
pH-Value	4.1 (0.2) [3]	4.0 (0.2) [5]	4.5 (0.2) [4]
pH group*	acid	acid	acid
Bulk density	0.27 (0.06)	0.24 (0.06)	0.24 (0.08)
Total porosity	(-)	90.3% (3.4%) [9]	92.3% (2.4%) [12]
Saturated hydraulic conductivity	1419 cm/day (2291 cm/day) [4]	366 cm/day (445 cm/day) [17]	62 cm/day (84 cm/day) [13]

*according to Succow & Joosten (2001)

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Related information

Information on AllWet-RES:

https://www.bodenkunde-projekte.hu-berlin.de/allwet/

Information on peatland substrates worldwide:

http://www.mire-substrates.com/

Information on hydrogeomorphic wetland units:

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