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Development and persistence of an African mire: How the oldest South African fen has survived in a marginal climate

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ABSTRACT

Hydrological processes maintain wetlands, whose position in the landscape determines their character and possible response to climate change. We studied such responses to long periods of climate change in a large groundwater fed fen (Mfabeni Mire), which is one of the oldest fen systems in South Africa. The geological and geomorphological setting of the mire was studied as well as its stratigraphy and chronology. The basal peat of the mire was at a depth of 9.9 m dated at ca. 44,000 cal years Before Present (BP). The average accumulation rate during the Late Pleistocene was 0.15 mm/year. During the Holocene it was higher (0.3 mm/year). Despite climate change over this period, peat formation has hardly been interrupted, suggesting that the system has been able to almost continuously sustain peat formation processes. This is possible because the peatland is situated in a valley that is bordered by a highly permeable sand dune cordon with an elevated groundwater table that directs groundwater towards the mire. The infilling of the valley by peat has resulted in a basin with lower permeability than in the surrounding dunes, forcing the water table in the adjacent aquifer to rise, thus ensuring the mire system a supply of groundwater that is large enough to dampen the effects of climatic variation.

1. Introduction

Peatlands, which comprise about 50% of the world's wetlands (Joosten and Clarke, 2002; Mitsch and Gosselink, 2000), are rare in semi-arid and arid areas such as southern Africa (Grundling and Grobler, 2005; Scott, 1982), and are often threatened by human development, mainly for agriculture (Cowan and Van Riet, 1998; Grobler et al., 2004). Consequently they are of high regional importance, and require good management, which is challenged by the poor understanding of their ecological and hydrological functions. Peatlands are ecohydrological systems where there are strong feedbacks between vegetation and local precipitation, evapotranspiration, surface and groundwater flows (Emili and Price, 2006; Ingram, 1983), in which the peat substrate comprises the incompletely decomposed vegetation that grows there. Both the magnitude and source of water fluxes, the associated supply of dissolved minerals and nutrients influence the vegetation response and determine the peatland form and function (Ivanov, 1981; Rydin and Jeglum, 2006). Many peatlands in semi-arid areas are fens, which are peatlands mostly located in valley bottoms (topogenous), but sometimes on slopes (soligenous), that receives their water input from precipitation, surface inflow and especially groundwater inflow (Joosten and Clarke, 2002). Consequently, they are minerotophic and often nutrient-rich reflecting predominant surface and groundwater sources (Clymo, 1983; Rydin and Jeglum, 2006).

Most peatlands in the northern hemisphere developed during the Holocene since the last glaciation, and in that climate accumulated peat at 0.3–0.55 mm/year (Borren et al., 2004; Gorham et al., 2003). In non-glaciated areas peatlands of Late Pleistocene age have been reported (Irving and Meadows, 1997; Wüst et al., 2008) with accumulation rates ranging from 0.5 to 2 mm/year (Dommain et al., 2011; Hope et al., 2005). Differences in peat accumulation result from variations in climate, duration and level of inundation and dominant vegetation type. The most rapid accumulation is often in *Sphagnum* dominated systems, because of its resistance to decay. However, there is also substantial peat accumulation in sedge- (Chimner and Karberg, 2008) or tree dominated systems (Dommain et al., 2011), including in semi-arid or tropical peatlands (Lappalainen, 1996).

Many northern peatlands have a predictable succession from sedge to moss-dominated vegetation arising because peat accumulation, and the resulting rise in water table, changes the strength and source of water inputs (Ivanov, 1981; Lapen et al., 2005). In semi-arid peatlands the accumulation of peat can also affect the hydrology (Norström et al., 2009) but the elevation to which peat can accumulate relies more strongly on the availability of water from surface or groundwater

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sources. Kulczyñski (1949) indicated in a study of Polesian peatlands that the accumulation of peat in lowlands could result in a rise of regional groundwater levels, whilst Emili and Price (2006) noted that a higher regional water table will favour peatland expansion in a hypermaritime forest–peatland complex, western Canada. In a study of peatlands on the Ruoergai Plateau, in China, Schumann and Joosten (2007) established that the accumulation of peat in lowlands impeded water flow and caused a rise of the water table in the mires which caused a rise of the groundwater in the adjacent upland, thereby facilitating continuous peat accumulation during the Holocene. However, Ellery et al., 2012; Grundling et al., 2000 concluded that peatland formation in floodplains in tropical and subtropical regions such as Maputaland, South Africa, is part of backwater and aggradational (the accumulation of sediment sequences) floodplain processes.

The development of peatlands is strongly linked to hydrological processes from the pore-space to landscape level (Price, 2003). The persistence of peat-accumulating wetlands (mires) in semi-arid settings and/or environments with strongly seasonal rainfall, which is common throughout southern Africa, requires water inputs from large catchments or sustained local groundwater input (Colvin et al., 2007; Ellery et al., 2009; Meadows, 1988). Groundwater inflow, being less temporally variable than precipitation in marginal climatic settings where rainfall is strongly seasonal and evapotranspiration exceeds precipitation, provides a relatively constant water source that is likely to sustain permanently wet conditions (Kurtz et al., 2007). It is therefore important to determine the nature and importance of surface–groundwater interactions in landscapes where rainfall is seasonal and exhibits high inter-annual variability. Furthermore, given the wide interest in climate change and its expected impact on wetlands (Crooks et al., 2011; Joosten, 2009), it is necessary that management guidelines are based on a sound understanding of the development and functioning of these systems.

Groundwater flow to peatlands is governed by its catchment's topography, geology and the storage and transmission properties of the geologic materials and soils (Dingman, 2002; Freeze and Cherry, 1979). Topography can contribute to complex patterns of groundwater flow into peatlands (Lapen et al., 2005; Winter, 2001) where a landscape with prominent or high relief will develop local flow systems compared to relatively simpler regional flow systems in a flatter landscape (Winter, 1999). Geologic controls on groundwater movement include stratigraphic variability in the case of unconsolidated lithologies, or structural and lithological controls in the case of consolidated sediments (Le Maitre and Colvin, 2008). Preferential flow will typically take place in or along permeable layers, contact, faulting and folding zones (Dingman, 2002; Freeze and Cherry, 1979). It is therefore important to understand the geological setting and stratigraphic characteristics of a peatland and the surrounding landscape, as these factors affect groundwater flow into and within the wetland (Winter, 1999). Sustained groundwater flow is vital for survival of obligate species and the maintenance of anaerobic conditions necessary for peat accumulation in regions with large water deficits as in marginal climates. This study focuses on the development of the Mfabeni Mire, an 11 m thick peat deposit in a valley-bottom setting in South Africa. The objectives of this study are to 1) assess the development of this mire system in relation to the landscape position and 2) understand the hydrological conditions in which the mire could survive in spite of a large regional water deficit.

2. Study area

The Mfabeni Mire is located on the Eastern Shores of Lake St. Lucia, an area between the Indian Ocean in the east and Lake St. Lucia to the west, within the catchment of the Mkuze River (Fig. 1). The region of the entire coastal plain in northern KwaZulu-Natal is known as Maputaland and has a subtropical climate with hot and humid summers and mild, drier winters where frost rarely occurs (Taylor, 1991). The mean summer temperature (November to March) exceeds 21 °C with 60% of the annual rainfall occurring in summer (Mucina and Rutherford, 2006). The mean annual precipitation of the Eastern Shores decreases from 1200 mm/annum in the east on the coast to 900 mm 10 km westwards across Lake St. Lucia (Taylor et al., 2006).

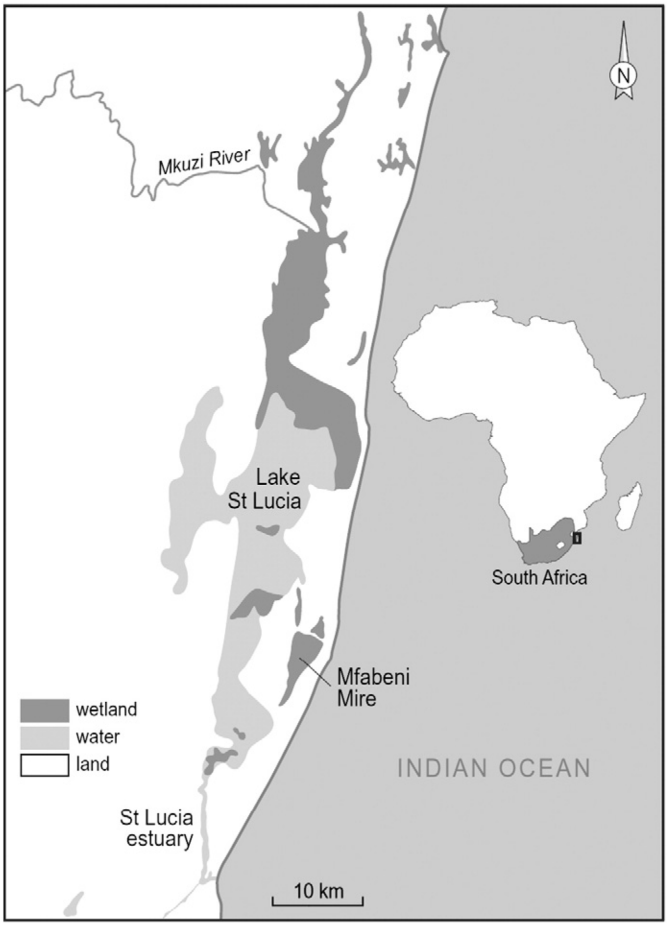

Fig. 1. The location of the Mfabeni Mire in South Africa.

Wetlands, ranging from seasonally inundated depressions to permanently wet mires and swamp forests are common (Fig. 1), whilst coastal dune forest and wooded grassland dominate terrestrial areas (Goge, 2003; Grundling et al., 1998; Venter, 2003). In the recent past, the dunes surrounding Mfabeni Mire supported exotic *Pinus* plantations that were planted for commercial timber production, but these trees were removed in the early 2000s. Wildlife conservation and tourism are now the primary designated land use activities. The Eastern Shores comprises high coastal sand dunes and low-lying plains located on the Maputaland primary aquifer, which hosts one of the highest concentrations of wetlands in South Africa and the greatest extent of swamp forests, which are common in the region but rare in South Africa (Grundling et al., 1998). Within the low-lying plain occurs the Mfabeni Mire, bordered in the east by an 80–100 m high coastal vegetated dune cordon and in the west by the older 15–70 m high Embomveni (Western) dune ridge (Davies et al., 1992). The peatland is ca. 10 km long, 3 km wide in places and comprises 1462 ha (31% of the 4636 ha of the topographically defined catchment). It is triangular with the main surface drainage within the swamp forest on its western edge, flowing southwards to Lake St. Lucia, and is bound by beach ridges in the north and south separating it from Lake Bhangazi and Lake St. Lucia, respectively. Minor intermittent water exchanges to or from Lake Bhangazi occur depending on lake levels, which vary depending on wet and dry climate cycles. The Mfabeni Mire is dominated in the north and east by reed/sedge vegetation communities with sparse occurrence of *Sphagnum* (less than 10% of the peatland), and in the south and west by swamp forest (Grundling et al., 1998) that achieves its maximum extent across the peatland towards the centre of the system.

The idealised geology of the Eastern Shores, as derived from Davies et al. (1992), Johnson and Anhauesser (2006), Botha and Porat (2007), and Porat and Botha (2008), consists of Jurassic rhyolites and basalts of the Lebombo range, which are overlain by Cretaceous siltstones of the Zululand Group. An unconformity (a break in a stratigraphic sequence) exists between the Zululand Group and the younger Port Durnford Formation of Middle Pleistocene age consisting of lacustrine mud and clayey carbonaceous sand. The overlying Pleistocene sands and sandstones (Kosi Bay, Isipingo and KwaMbonambi Formations) and Holocene sands (Sibayi Formation) are well sorted, highly porous and permeable. The older KwaMbonambi Formation forms the lower Embomveni (Western) dune ridge, whilst the younger Sibayi Formation covers the Kosi Bay formation to form the higher coastal dune in the east. The Mfabeni peat has accumulated in the valley between these two dune ridges.

3. Methods

The geology of the dunes adjacent to the Mfabeni Mire was examined at 7 terrestrial sites (Fig. 2) by reverse circulation drilling (Sites A6, B3, D3, DWAF-A, UW1E1, UW2E1 and UW2W1). The lithology of each core was described in the field according to grain size, texture and colour. This investigation was intended to supplement previous geological investigations of the coastal plain including the Eastern Shores (Geological Survey, 1985a,b) by Davies et al. (1992), and to determine the extent of any impeding layers beneath and/or adjacent to the Mfabeni Mire.

The peatland was cored along eight east–west transects that were spaced 800 to 1600 m apart from south to north. The borehole spacing along transects was between 100 and 200 m. Peat was sampled with a Russian peat corer at 0.5 m increments, one half of which was described in the field according to the Von Post humification scale (Von Post, 1922) and the remainder sealed and returned to the laboratory to determine ash content. Samples were dried for 12 h at 105 °C in an Optolab Term-o-mat 321 oven, and ashed at 815 °C for 3 h in open ceramic crucibles in a Carbolite CSF furnace.

C^{14} dating of selected peat samples was performed by the Council for Scientific and Industrial Research laboratories in Pretoria, South Africa. The C^{14} age determinations are given in years before present. Dates are reported in conventional radiocarbon years, i.e. using a half-life of 5568 years for C^{14}. Ages are corrected for variations in isotope fractionation and ages are calibrated for the southern hemisphere using the Pretoria Calibration Programme (Talma and Vogel, 1993).

4. Results

4.1. Basin geology

Coring in and adjacent to the Mfabeni Mire established that grey clay material occurs approximately at present day sea-level. In the middle of the mire (transect M8), the clay material below the base of the peat is at least 6 m thick (Fig. 3), but the bottom of the deposit was not reached. At the deepest point sampled some silt was present in the clay. Coring at 7 sites adjacent to the peatland to depths below sea-level showed that the clay material does not extend beyond the width of the Mfabeni Mire valley-bottom (Fig. 3), but it might extend along the length of the peatland.

The cover sands adjacent to the Mfabeni Mire (boreholes UW1E1 and UW2E1 to the east and UW2W1 and D3 to the west) are well

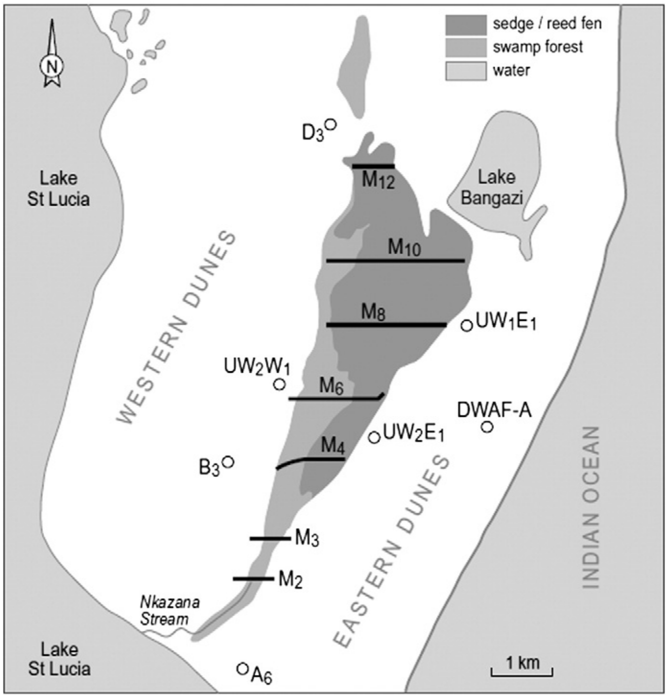

Fig. 2. Sample sites in and adjacent to the Mfabeni Mire.

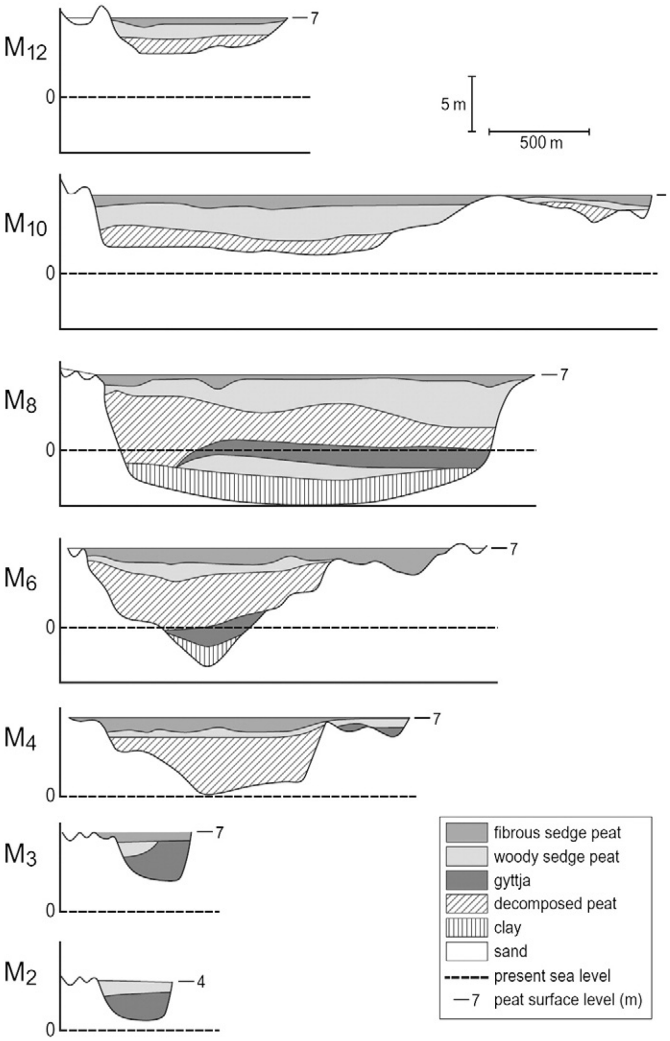

Fig. 3. Stratigraphy of the Mfabeni Mire along eight transects from west to east.

sorted and contain typically less than 5% clay in the upper layers. However, the clay content increases more rapidly with depth in the older western dunes (UW2W1 and D3) than the younger eastern dunes (UW1E1 and UW2E1). The sand in the boreholes adjacent to the central part of the peatland (UW2W1 and UW2E1) contains elevated clay and organic contents at a depth that equates to the present sea-level, but it is not comparable to the clay material beneath the peatland in either its thickness or clay content. Clay was found in the far northern and southern boreholes (D3 and A6 respectively; Fig. 2), but at a greater depth than the clay beneath the Mfabeni Mire (14 m below mean sea-level).

4.2. Morphological characteristics Mfabeni Mire

The Mfabeni Mire has a complex morphology occupying a deep central depression that is oriented north–south, and with smaller depressions east and west of the main depression. In the main basin the peat body is up to 10.8 m thick, whilst in the lateral basins the peat depths do not exceed 2.5 m (Fig. 3). The surface of the peatland slopes downwards from the central region of the peatland in a southerly direction, and also has a very gentle slope downwards from West to East (not shown). Between transects M3 and M2 the peat surface steepens with the present Nkazana stream channel incised into the peat surface draining towards Lake St. Lucia (Fig. 2).

4.3. Peatland stratigraphy

Variation in the fibre, organic and ash contents within the peat are relatively consistent down the length and across the width of the peatland. The number of layers and the complexity of their configuration are greatest where the peat is thickest (Fig. 3).

A total of five distinct peat layers are recognised (Fig. 3). The basal peat layer in transect M8 is resting on the clay material and consists of brown medium fibrous wood and sedge material (Von Post scale 4), with some sand and a thin ash layer. This peat is covered by a darker very fine-grained gyttja layer with some secondary layers of sand and more fibrous peat. The gyttja layer is overlain by a dark, medium fibrous layer with wood and sedge remains (Von Post scale 4), which in turn is covered by a decomposed dark sedge peat (Von Post scale 6). Higher in the profile a less decomposed fibrous sedge peat with some wood remnants was encountered (Von Post scale 3). A thin layer of iron nodules and wood chunks separates this layer from the top 1 m layer of peat. The top layer consists of a very poorly decomposed sedge and woody peat (Von Post scale 1 to 2); it is more fibrous than all lower peat layers. Occasionally, sandy layers of about 0.2 m separate the peat layers (data not shown), in particular in the eastern part of the peatland in the decomposed peat layer (Fig. 3). In the western part of the mire and in the more shallow peat deposits in the north, thin ash layers occur (data not shown).

4.4. Radiocarbon dating

The radiocarbon dating of the bottom peat at 9.9 m indicates that peat growth started about 44,000 cal years BP, which is very close to the detection limit of C^{14} dating (Van der Plicht and Hogg, 2006). The contact between the basal peat layer and the underlying clay was dated at 43,000 + 4900 to −3000 cal years BP. An older date of 45,100 + 4900 to −3000 cal years BP was determined for the peat 2 m above the basal peat, but this is within the error range of the dating method. Therefore, we estimate the start of the peat growth at about 44,000 cal years BP. The age–depth curve of the M8 profile (Fig. 4) based on eight radiocarbon dates shows a very slow accumulation rate between 45,000 and 10,000 cal years BP. After 10,000 cal years BP, which marks the Pleistocene–Holocene boundary, the accumulation rates increased considerably (Fig. 4). Two additional dates (not shown) were obtained for core M10-10 in order to date a 0.47 m thick ash layer. The peat at 4.35 m, immediately below the ash layer was, dated at 25,700 ± 410 years BP and the age above the ash layer was 12,430 ± 120 years BP.

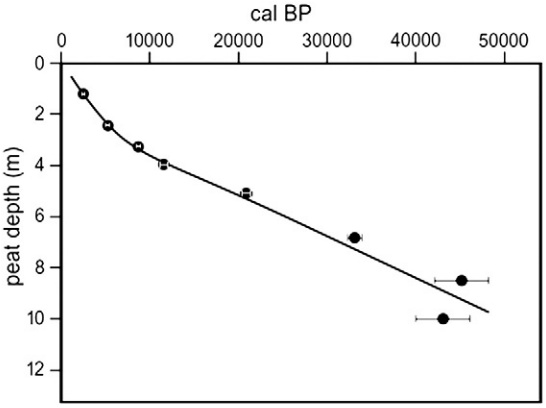

Fig. 4. This figure will be replaced by a new Fig. 4. Age–depth curve of Mfabeni Mire, South Africa, based on C^{14}-dating of a profile in the centre of the M8 profile (see Fig. 2). A distinct increase in peat accumulation rate can be observed after 10,000 BP, which is the Pleistocene–Holocene boundary.

5. Discussion

5.1. The geological setting of the Mfabeni Mire

The Mfabeni Mire peat is located on clay material within a valley-bottom setting (Fig. 3). The peat deposit thins out to the south and the north where it is underlain by reworked aeolian marine sands. The development of the Mfabeni Mire's depositional setting in relation to sea-level change is presented in Table 1. Through the Late Pleistocene the sea-level fluctuated 5–7 m above the present sea-level during the last Interglacial High Stand from ca. 115,000–90,000 years BP (Ramsay and Cooper, 2002).

The valley-bottom in which the peat has formed probably represents the southward course of the Nkazana paleo-channel, a tributary of the Mkuze River (Fig. 1). The valley may have undergone several phases of erosion that accompanied rejuvenation of coastal rivers during and since the last Interglacial High Stand until the Last Glacial Maximum, ca. 18,000 years BP (Taylor et al., 2006; Wright et al., 2000). The Nkazana paleo-channel was probably incised into Early Pleistocene estuarine/lacustrine mud and carbonaceous sand of the Port Durnford Formation (Taylor et al., 2006; Wright et al., 2000), with the clay material underlying the Mfabeni Mire of lacustrine or intertidal origin. This lacustrine or intertidal material was deposited since the last Interglacial High Stand period in this tributary following blockage of the tributary valley with clastic sediment during the ongoing aggradation along the Mkuze River. During the Late Pleistocene this aggradation resulted in the shifting of the Mkuze River estuary to the south to form a combined mouth with the Mfolozi River (Wright et al., 2000). The blockage of the Nkazana channel raised the base level and established an ideal low energy environment for the accumulation of peat as is described for similar but younger upstream environments in the Mkuze River floodplain by Ellery et al. (2012).

Results from the terrestrial boreholes indicated that the clay layer is restricted to the valley-bottom in an east–west direction (Fig. 3). It is possible that the clay layer extends further north and south but this was not investigated. This clay material plays an important role in the formation and development of the Mfabeni Mire by preventing water losses from ca. 45,000 years BP when sea-level was about 50 m below current sea-level (Ramsay and Cooper, 2002) to ca. 6500 years BP (Table 1) when the present sea-level was reached (Ramsay, 1995).

Table 1
Development of the Mfabeni Mire depositional environment in relation to sea-level change from the Late Pleistocene to the Holocene. Geological information older than 65,000 years BP is according to Ramsay and Cooper (2002), whilst information younger than 65,000 years BP is according to Ramsay (1995).

Years BP	Sea-level	Mfabeni Mire's depositional environment Note: all elevations are levels relative to present sea-level (PSL)
300,000	+5	High stand — Formation of western dune complex
200,000	−150	Incising of coastal rivers
125,000	+5–7 m	Last Glacial High Stand — deposition of Isipingo beach rock and sediments forming the core of the eastern Dune complex
118,000	−45 m	Incising of coastal rivers and Nkazana tributary to −10 m PSL and deeper
95,000–115,000	+5–7 m	Last Glacial High Stand — Deposition of Isipingo beach rocks, core of the eastern Dune complex Deposition of clay layer to 0 m (PSL). Formation of beach terraces in Mfabeni basin? Incising clay layer to −4 m PSL? Formation of beach ridges in Mfabeni Basin?
45,000	−45 m	Peat accumulation starts in Mfabeni Basin at −4 m PSL?
33,000	−62 m	Peat accumulation reaches 0 m (PSL) in the Mfabeni Basin
18,000	−125 m	Incising of coastal rivers NOT Nkazana tributary. Peat at 2 m PSL.
12,500	−95 m	Northern part of basin experiences peat fire. Rest of basin peat at 3 m PSL.
10,000	−50 m	Pleistocene/Holocene boundary at 3 m. 20–50 cm sand layers in peat (central). Ash layers in north and south at 3.5 m PSL.
6500	0 m	Peat accumulation reaches 4.5 m PSL in the Mfabeni Basin
4400	+3.5 m	Peat accumulation reaches 5.0 m PSL in the Mfabeni Basin.
3000	−2 m	Peat accumulation reaches 5.5 m PSL in the Mfabeni Basin. Some ash layers in the northern section
1500	+1.5 m	Peat accumulation reaches 6 m PSL in the Mfabeni Basin
Present	0 m	Peat accumulation reaches 7 m PSL in the Mfabeni Basin

5.2. Chronology of the Mfabeni Mire

The various peat layers (Fig. 3) and plant remains in the Mfabeni Mire represent different environmental conditions. Regular occurrence of wood fragments may represent swamp forests, whilst sedges or grasses indicate more open herbaceous fen conditions. Peat fires, as represented by ash and charcoal in peat profiles, and the accompanying release of nutrients and minerals (Ellery et al., 1989) were probably instrumental in contributing to spatial heterogeneity in vegetation distribution within the Mfabeni Mire. Sedge remains in the clay beneath the Mfabeni Mire and wood remains in the basal peat (Fig. 3) point to the presence of riparian or swamp forest at the time when peat accumulation commenced in the Nkazana paleo-channel ca. 43,000 years ago. The occurrence of *Typha* throughout the pollen record as reported by Mazus (in Grundling et al., 1998) suggests the prevalence of fresh water conditions from this Late Pleistocene period until present. The presence of gyttja (Fig. 3) above this basal peat indicates flooding of the peat in that period, leading to the emergence of a shallow lake in the eastern and southern parts of the mire until ca. 33,000 years BP. This rather sudden increase in water levels was probably caused by the blocking of the Nkazana paleo-channel. The gyttja and peat layers are often interbedded with thin layers of sand (Fig. 3), representing periods of aeolian sediment transport and deposition (Wright et al., 2000).

After ca. 33,000 years BP a fen environment developed with peat accumulation derived mainly from sedges such as *Cladium mariscus*. Finch and Hill (2008) report the appearance of *Haloragidaceae* in the Mfabeni Mire pollen record between 30,000 and 20,000 years BP, which together with the dominance of *Cyperaceae* and the presence of pollen of aquatic species point to very wet conditions during this period (Grundling et al., 1998). Peat with a highly decomposed and finer texture with dispersed and thin layers of sand were deposited from ca. 20,800 years BP to ca. 11,570 years BP suggesting drier conditions at the onset of the last Glacial Maximum at ca. 21,000 years BP (Partridge et al., 1999). The shift towards a drier and cooler climate is also supported by the pollen record, with *Poaceae* becoming dominant, whilst *Cyperaceae* steadily declined (Finch and Hill, 2008). The presence of a prominent ash layer at M10 (Fig. 2) between 4.35 and 3.88 m above sea-level further supports the idea of a drier climate.

The periods of aeolian sedimentation in the peatland ceased in the early Holocene, suggesting wetter conditions and increased vegetation cover that would have stabilised the soil surface. A rapid increase in pollen of wetland species (*Cyperaceae*) in the Holocene suggests wetter conditions and a rise in water level in the peatland. The alternating layers of finer and fibrous peat from the early to middle Holocene (ca. 5280 ± 70 years BP) represent wetter conditions such as open sedge fen (sedge peat).

Chunky wood layers with in the upper woody sedge layer (Fig. 3) present in the western and central part of the wetland shows that by ca. 2450 ± 50 years BP most of the peatland was covered by swamp forest. After that a fibrous sedge peat layer developed, reflecting a sharp decline in swamp forest cover, with practically all swamp forest giving way to open sedge fen over the next 2500 years, probably due to wetter conditions in the fen as a result of an increase of groundwater discharge from the surrounding dunes. The current distribution of the swamp forest (Fig. 2 — only in the western and southern parts of Mfabeni Mire) indicates that the swamp forest has expanded again during recent periods, possibly due to slightly drier conditions in the fen as a consequence of incision along the Nkazana stream, which has developed along the relatively steep slope between M3 and M2.

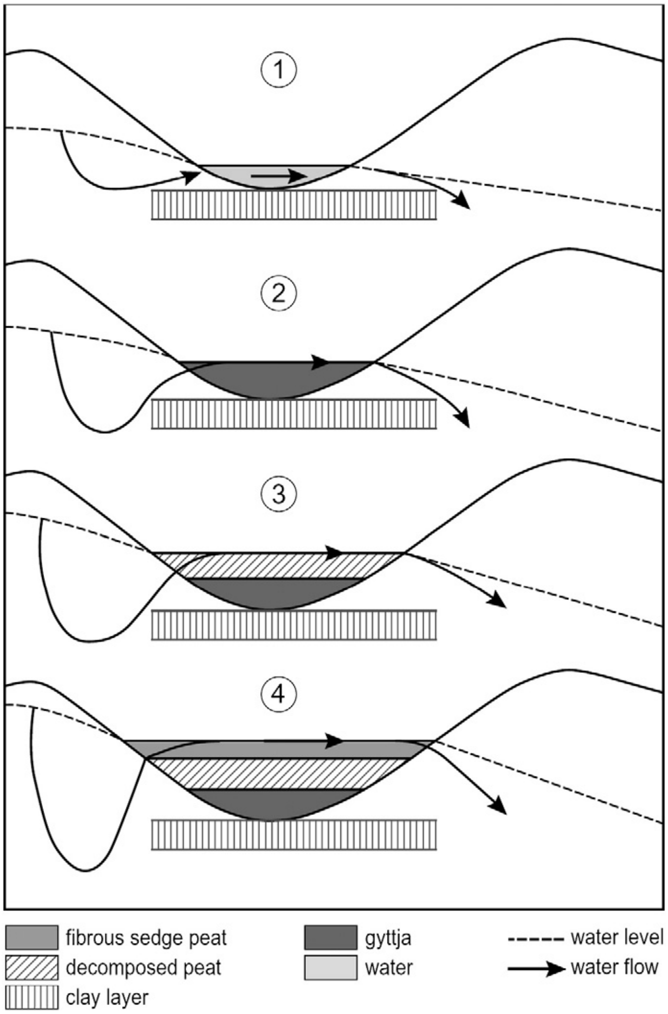

Fig. 5. Possible changes in groundwater flow during peat accumulation in Mfabeni Mire.

5.3. Peat accumulation rates

On the basis of peat thickness (depth) and radiocarbon dating, two distinct trends are reflected in the accumulation rates for the Mfabeni Mire: 0.15 mm/year during the Late Pleistocene and 0.3 mm/year during the Holocene (Fig. 4). The Pleistocene/Holocene boundary clearly coincides with an increased peat accumulation rate in the Mfabeni Mire. The different accumulation rates are likely to be a reflection of the different environmental conditions in the Late Pleistocene and Holocene as described above indicating that the conditions during the Holocene were more favourable for peat accumulation than conditions during the Late Pleistocene. It is of interest that the Mfabeni Holocene peat accumulation rate of 0.3 mm/year is considerably lower than younger Holocene peatlands of this region reported by Grundling et al. (1998), which may vary between 0.9 and 2.1 mm/year, with an average of 1.1 mm/year. However, the accumulation rate is similar to the global average accumulation rates for Holocene peatlands in the Northern Hemisphere of 0.3–0.55 mm/year (Joosten and Clarke, 2002; Verhoeven et al., 2006).

5.4. A conceptual model of the Mfabeni Mire hydrology

The inundated clay-bottom valley, which was formed in backwater conditions, where a low energy environment prevailed probably due to aggradation of the Mkuze River as well as the Mfolozi River floodplain to the south (Grenfell et al., 2009, 2010), produced a hydrogeomorphic setting suitable for initiation of peat formation in the Nkazana paleo-valley ~44,000 cal years BP. We hypothesise that changes in groundwater flow patterns on the Eastern Shores, east of Lake St. Lucia (Fig. 2), over time are due to peat accumulation in the Mfabeni Mire as represented in Fig. 5. Groundwater discharge from the western dune accumulated in the valley-bottom to initially form a shallow lake on the basal clay layer, with some of the water flowing towards the east and recharging the groundwater below the eastern dune (Fig. 5-1). This phase was followed by gyttja deposition in the open water (Fig. 5-2), colonisation of the surface by vegetation and subsequent infilling of the valley-bottom with peat (Fig. 5-3) which has a lower hydraulic conductivity than the surrounding sandy reworked marine deposits (Fig. 5-4). The presence of a barrier such as this to the lateral flow of water caused the groundwater table in the western Embomveni dune cordon to rise, accompanied by prolonged inundation of the peatland, promoting further peat accumulation. Over time there must have been a steepening of the groundwater surface east of Mfabeni Mire (Fig. 5-4) as the mire surface level (and water table) rose with respect to sea-level on the extreme eastern margin of the eastern dunes (Fig. 5-4).

We further hypothesise that the Mfabeni Mire, because it is a groundwater fed system, has been able to cope with climate changes since its formation in the Late Pleistocene, by influencing the regional water table in the western dune cordon through infilling of the valley with peat. This process of infilling of with peat (Fig. 5) is thus a consequence of one or more of the following (Fig. 6): (1) the regional water table rising due to increased groundwater input (GW) during the Late Pleistocene; wetter conditions with higher precipitation (P); sea-level rise after the last glacial maximum, as well as the raising of the base level due to sediment aggradation. Wetter conditions likely increase water discharge (Q) into the Mfabeni Mire valley, (2) inundating the valley floor with surface water and saturating lower laying areas. Increased inundation of the land surface (3) results in increased plant growth and biomass production of fibrous plant tissue. Coupled with (4) a decrease in O_2 availability in the soil due to (2) inundation and saturation, decreased mineralisation rates (5) follow, promoting peat accumulation (6). The infilling of the valley-bottom with peat (7), which has a lower hydraulic conductivity than the sand of the surrounding terrain, results in a reduction in the eastward flow of groundwater from the west across the valley. As peat accumulates in the valley, the water table west of the valley rises (1), a positive feedback develops favouring peat accumulation. However, as the peat accumulates the peatland and surface vegetation expand laterally (8) in relation to basin morphology, resulting in (1) increased evapotranspiration losses [ET]. This negative feedback moderates the increase in discharge [Q] and controls the elevation to which peat is able to accumulate, because peat will accumulate to an elevation where average long-term inputs

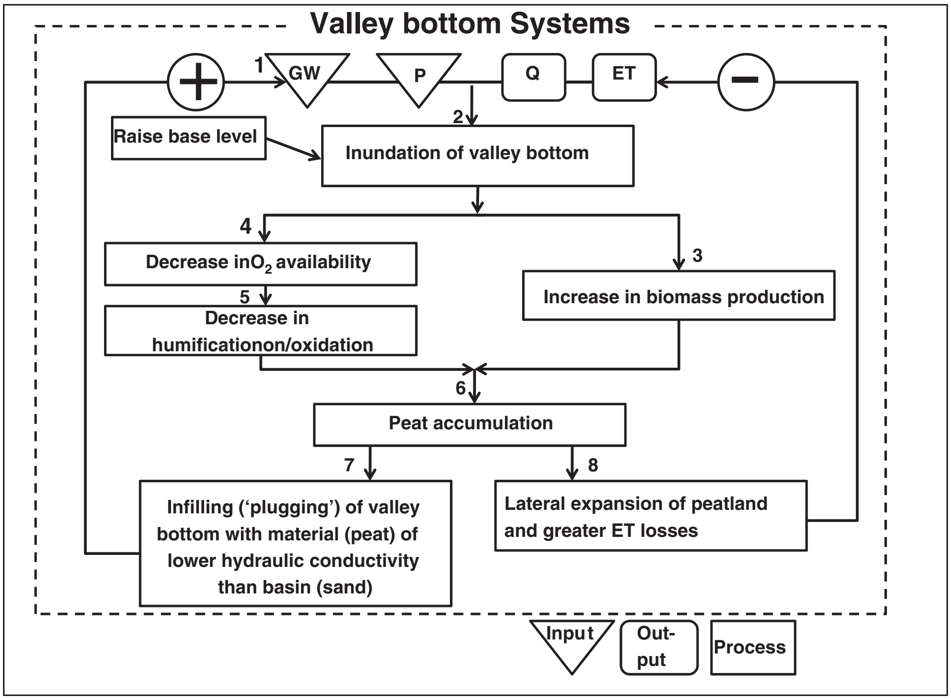

Fig. 6. A conceptual model of processes that contribute to peat formation of the Nkazana paleo-channel over extended time periods (tens of thousands of years).

and outputs are equal. This conceptual model indicates the importance of sustained groundwater discharge as a critical contribution of water to the system, providing sufficient wetness to maintain peat accumulation processes and dampening the effects of climatic perturbations.

6. Conclusion

The Mfabeni Mire is a groundwater dependant ecosystem that was formed in the Late Pleistocene and continued to develop during the Holocene. This paper shows that the infilling of a valley bottom with peat resulted in a plug effect which forced a rise in the elevation of the influent groundwater surface in the adjacent upland as peat accumulated in the lowland. In addition to favouring the development of a series of ephemeral non-peat wetlands adjacent to the mire, the consistent and permanent discharge of groundwater into the peatland from the upland allowed for the almost uninterrupted formation of peat over an extended period. This expansion of the groundwater source resulted in a buffering effect against climatic turbations in a semi-arid region providing a more stable localised environment for this mire to develop. Our ability to manage and conserve such systems in future will depend on the insight we gain in understanding the processes driving formation and evolution during periods of change. Further research on flow patterns within mires is needed to understand the mechanisms that can buffer groundwater fed fens against changes in climate.

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