Quantifying the water balance of Mfabeni Mire (iSimangaliso Wetland Park, South Africa) to understand its importance, functioning and vulnerability

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SUMMARY

Peatlands occurring in regions with high rates of total evaporation (*ET*), matching or exceeding precipitation (*P*) during seasonal dry periods or longer-term dry spells, are dependent on sustained groundwater flows to ensure peat accumulation. The objective of this study was to quantify the water balance of Mfabeni Mire in South Africa over one year, and thereby define its contribution to downstream and adjacent ecosystems and identify risks and consequences likely to arise from future shifts in the water balance.

P (1,031 mm) and *ET* (1,053 mm) dominated the water balance measured from May 2008 to April 2009. These were followed by groundwater inflows (14 mm), stream outflow (9 mm) and storage change (-3 mm, a net loss in water stored in the mire) with the smallest flux being groundwater outflow (0.3 mm). There were differences in the seasonal patterns of *ET* from the two dominant plant communities (swamp forest and sedge/reed fen), which probably resulted from their significantly different canopy structures. Limiting factors for *ET* were low vapour pressure deficit and cloud cover.

Although the water balance of Mfabeni Mire was dominated by and equally split between *ET* and *P*, it still contributed a small efflux to downstream ecosystems by streamflow. Its value in a landscape where seasonality and long-term dry periods are major ecological drivers lies in its damping effect on climatic variability. This creates a more stable environment for adjacent aquatic ecosystems by contributing to a steady groundwater condition. Mires occurring in areas that experience dry periods, where water stress frequently threatens biodiversity, should be recognised as assets in natural resource management; and their potential to support adjacent ecosystems should be protected through planning and conservation practices. Management of the area should include careful consideration of any proposed changes in land use or encouragement of one plant community at the expense of another, as such changes will alter the equilibrium of the water balance. Mfabeni Mire is particularly vulnerable through the impact of adjacent commercial forestry, which has impacted river and estuary management over the last 80 years and depleted groundwater levels in the surrounding aquifers.

KEY WORDS: groundwater; hydrology; peat; wetland

INTRODUCTION

The characteristics of wetlands vary considerably and are often determined by the nature of the exchanges represented by fluxes within the water budget (Baker *et al*. 2009, Gilvear & Bradley 2009). Calculating the water balance of a wetland can be complex, with large variation in error (Winter 1981, Benke *et al*. 2008). As for all wetlands, peatlands are an integral part of the hydrological cycle, with water balance components including precipitation (*P*), total evaporation (*ET*), surface flows and groundwater flows (Ingram 1983). Peat development is usually linked to the cool and moist climates of the temperate and boreal zones, where persistent water saturation occurs (Clymo 1983, Maltby & Proctor 1996). However, the interaction and magnitude of processes giving rise to peatlands in drier parts of the world, such as the sub-tropics of southern Africa, are poorly understood (Lappalainen 1996, Joosten & Clarke 2002, Grundling & Grobler 2005) and require further consideration to optimise the protection and management of these peatlands within their hydrological environments. In such regions, *ET* can equal or exceed precipitation during dry seasons or the dry phases (typically lasting 7–11 years) of longer-term dry–wet cycles (Tyson 1981, Mucina & Rutherford 2006, Riddell *et al*. 2013); and the mechanisms ensuring waterlogged and anaerobic conditions - and therefore peat accumulation - are more sensitive to the complexities of internal storage of water, its redistribution by surface and groundwater flows, and variability in *P*. Internationally it was concluded by Souch *et al*. (1996) that *ET* and the related physical processes of various wetland types are not well characterised. Furthermore, according to Drexler *et al*. (2004), *ET* remains insufficiently characterised due to the diversity and complexity of wetland types, despite the numerous methods that are available to quantify wetland *ET*. The most commonly studied wetlands in southern Africa have been seasonally saturated, reflecting intra-annual precipitation patterns (Tooth & McCarthy 2007, A.T. Grundling *et al*. 2013). The hydrogeomorphic setting strongly influences form and function. McCarthy (2000) used a water balance study to show that a small headwater wetland in the Zimbabwean Highveld (interior high-altitude grassland plateau) was not important in promoting downstream flow in dry seasons; and Riddell *et al*. (2013) found that *ET* from a headwater wetland was higher than from the surrounding catchment in summer and winter, so the wetland did not augment baseflows. These findings are contrary to the function of a headwater peatland in the Magalies Mountains of the South African Highveld, which released a significant baseflow contribution (Smakhtin & Batchelor 2005). Comparative studies from wetter temperate climates clearly indicate that wetlands can contribute to streamflow and groundwater recharge whilst their inflows are dominated by precipitation (e.g. ombrotrophic bogs) and spring snowmelt with associated overland flow (e.g. prairie potholes) (Baker *et al*. 2009). The differences in wetland function may reflect differences in annual weather patterns or, more likely, differences in local landscape and lithology which control water stores and flows (Stolt *et al*. 2000). This is particularly important for the development of peat-forming wetlands, which require sustained wet conditions and occur where the climate is less seasonal (shorter dry periods) or in locations with sustained groundwater discharge (P. Grundling *et al*. 2013). For example, Ellery *et al*. (2012) found that peat accumulation on the Mkuze floodplain is largely a consequence of sustained groundwater flow, and the peatland itself is not a source of water but simply an area where discharge occurs.

In a recent ten-year drought (2001–2011) Mfabeni Mire in iSimangaliso Wetland Park (eastern South Africa) was found to provide diffuse freshwater seepage along the banks of the Eastern Shores of Lake St. Lucia and critical refugia for organisms threatened by the hypersaline conditions in the lake (Taylor *et al*. 2006). Clearly the mire plays a vital role in the linked ecosystem of the lake, and quantifying the water balance of Mfabeni Mire is critical to advancing our understanding of its ecohydrological function. This is especially important because rainfall is variable and extended drought conditions occur, since linked ecosystems can be strongly affected by the water contributions of adjacent or upstream wetlands. Consequently, the objective of this study was to quantify the water balance of Mfabeni Mire. The ultimate aim of the work was to provide the authorities and policy makers who control and manage the wider area with information that would enhance their decision-making ability in relation to groundwater abstraction, land-use zoning (e.g. establishment of timber plantations), burning regimes and vegetation succession.

SITE AND HYDROLOGICAL SETTING

Mfabeni Mire (28º 9.007′ S, 32º 31.492′ E), a 1462 ha sedge/reed fen and swamp forest peatland, is located on the eastern seaboard of South Africa, close to sea level in a low-lying topographical depression (Figure 1). It is bordered to the east by an 80–100 m high vegetated coastal dune cordon (known as the eastern dunes) and to the west by the 15–70 m high Embomveni sand dune ridge (known as the western dunes). Sedge/reed fen vegetation communities (0.3–1.5 m tall) cover the northern and eastern parts of the mire and include the sedges *Cladium mariscus*, *Fimbristylis bivalvis*, *Rhynchospora holo-schoenoides and Phragmites australis* with the grasses *Panicum glandulopaniculatum* and *Ischaemum fasciculatum* (Figure 2). The vegetation of the western and southern parts of the mire is swamp forest with an intermediate canopy 6–15 m above ground level (Figure 2). The dominant species are *Syzygium cordatum* and *Stenochlaena tenuifolia* in the northern parts of the swamp forest, *Ficus trichopoda* and *Nephrolepis biserrata* in the central parts, and *Barringtonia racemosa* and *Bridelia micrantha* in the southern section where streamflow occurs (Venter 2003). *Syzygium cordatum* trees grow up to 30 m with the fern *Stenochlaena tenuifolia* (Blechnaceae) climbing up the tree stems to a height of approximately 10 m (Figure 2), whilst an impenetrable stand of another fern (*Nephrolepis biserrata*), approximately 2.5 m tall, covers the forest floor (Clulow *et al.* 2013).

The main source of water in the catchment is precipitation. Taylor *et al*. (2006) reported a strong rainfall gradient, decreasing south-westwards from the coastal dunes towards Lake St Lucia. The mire is an extensive fen that has accumulated 11 m of peat during the past 44,000 years (Grundling *et al*. 2000), on a basal clay layer within an incised valley bottom

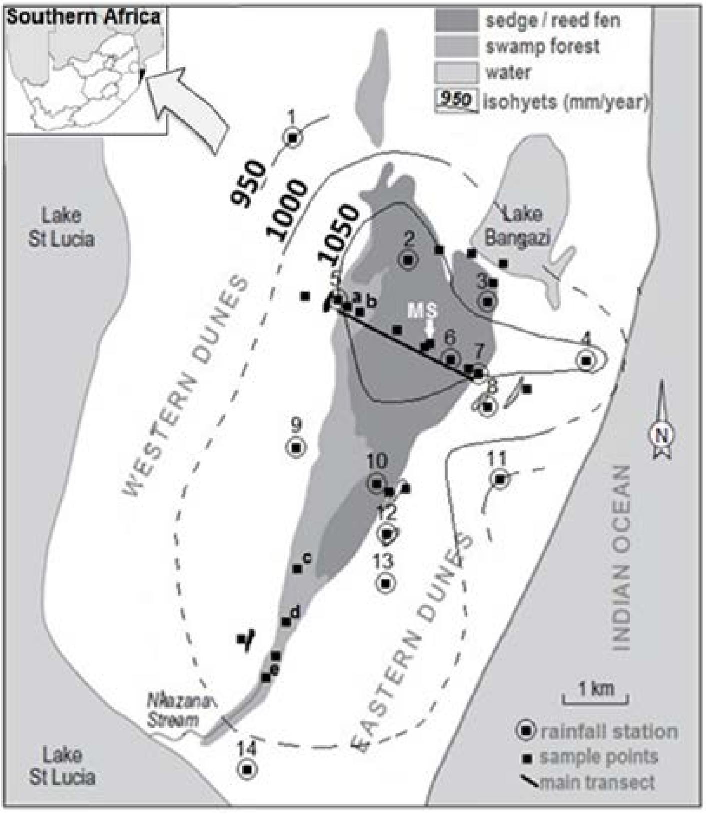

Figure 1. The study area. Rainfall stations and the main transect are indicated. Note the position of the meteorological station (MS). The spatial distribution of rainfall from May 2008 to April 2009 derived in this study (see Methods) is superposed. Dashed isohyets represent areas of greater uncertainty in the interpolation.

comprising reworked dune sands (Clulow *et al*. 2012b). It is bound to the north and south by beach ridges that separate it from Lake Bangazi and Lake St. Lucia, respectively (P. Grundling *et al*. 2013). Surface drainage *via* the Nkazana Stream is mainly southwards to Lake St. Lucia with minor intermittent water exchanges to or from Lake Bangazi depending on lake levels (Hart & Appleton 1997). The regional water table slopes from the western dunes towards the peatland and from the peatland towards the Indian Ocean (Rawlins & Kelbe 1991). Within the sedge/reed fen section of the peatland the water table slopes gently downwards to the east, then drops away sharply between the eastern edge of the peatland and the coastal dune. The abrupt steepening of the water table gradient is due to a sudden change in the underlying geological strata, where the clay lens and (probably) other discontinuous minor aquitards that impede vertical seepage losses from the mire give way to the younger, more permeable cover sands of the eastern dune cordon (Taylor *et al*. 2006).

Groundwater discharges from the regional groundwater mound below the western dune complex (the primary recharge area) into the peatland within the seepage area defined by the swamp forest (P. Grundling *et al*. 2013). The fen receives groundwater *via* the swamp forest and also directly from the western dune mound (Rawlins & Kelbe 1991). This groundwater discharges towards the central area of the peatland, after which it moves over the mire surface and in shallow subsurface layers along the gentle slope to the east (Grundling 2014). It is postulated that surface and shallow subsurface flows along the gradient are critical in keeping the peatland wet and maintaining its functions, as deeper groundwater contributions through the peat are limited by its very low hydraulic conductivity (P. Grundling *et al*. 2013). The groundwater is recharged as it moves towards the eastern section of the peatland, then follows a more steeply sloping water table outside the wetland, eastwards towards the coastal dune complex (Grundling 2014). Surface water in the southern section of the peatland is captured by the Nkazana Stream within the swamp forest, and drains southwards to Lake St. Lucia. Total evaporation plays a significant role in the hydrology of Mfabeni Mire and has been shown to exceed rainfall during droughts (Clulow *et al*. 2012b).

Figure 2. The main vegetation types covering the Mfabeni Mire: the sedge fen with the metrological station (top left); the swamp forest (right); and the western edge of the swamp forest (bottom left).

METHODS

Water balance assumptions

The water balance within a peatland depends on numerous flow and storage processes, internal and external to the mire. It may include precipitation, flow in surface streams, groundwater flow to and from underlying aquifers, seepage of water through peat, flows through pipes and fissures within the peat and adjacent substrata, diffuse flow over the peat surface, unconfined flow in directed channels, and ET (Ivanov 1981). In our study, various components of the water balance were measured and modelled using a variety of hydrometric techniques.

According to Ingram (1983), the water balance of a peatland such as Mfabeni Mire (see Figure 3) is expressed by [1]:

$$P + GW_{in} + S_{in} - ET - S_{out} - GW_{out} - \Delta V - \eta = 0$$

where P is precipitation (rainfall in this study), GW_{in} is groundwater seepage influxes, S_{in} is diffuse surface inflow and/or open channel inflow, ET is total evaporation, GW_{out} is groundwater seepage outflows, S_{out} is diffuse surface outflow and/or open channel outflow, ΔV is the change (increase reckoned positive) in stored water, and ŋ is an error term which can be high and uncertain.

In water-scarce regions and in subtropical areas with persistent droughts, ET frequently dominates the water balance (Clulow *et al*. 2012a). Therefore, it is important to understand and quantify ET and the contributions of different wetland vegetation types to the ET component of the Mfabeni Mire water balance. Where high ET rates persist during droughts, causing the water table in the peatland to drop, changes in peat volume reflected by peat surface oscillation (PSO) could be important in calculating water storage changes (Price & Schlotzhauer 1999); but significant PSO, as monitored against basal piezometer pipes and a PSO monitoring station, was not noted during the study period (Grundling 2014). It must also be acknowledged that our water balance study covered only a single year (May 2008 to April

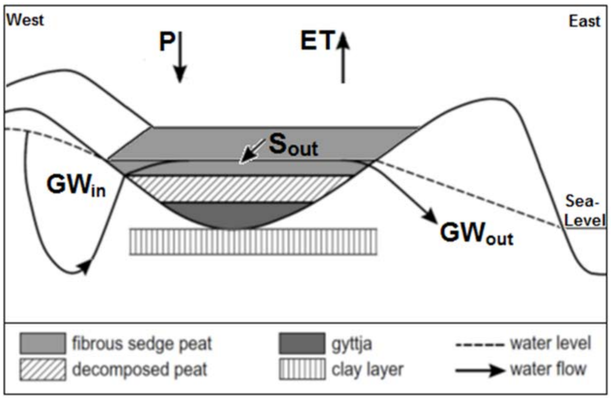

Figure 3. Schematic diagram of the basic assumptions underlying construction of the water balance for Mfabeni Mire. There is no stream inflow because the site is located in the headwaters of the Nkazana Stream.

2009) and that a longer study period encompassing the variability of dry–wet cycles would be beneficial.

For this study, groundwater inflows and outflows linking Mfabeni Mire with adjacent landscape units were measured on the ‘main transect’ which crossed swamp forest and fen on the widest part of the mire (Figure 1). Groundwater inflow occurred from the western dunes, and groundwater outflow from the eastern portion of the mire beneath the coastal dune complex to the east (Grundling 2014). No surface inflow occurred during the measurement period. Stream outflow did occur (southwards through the Nkazana Stream), and water storage changes in the peat were manifest as water-table fluctuations. Groundwater discharge northwards to Lake Bangazi was disregarded as it occurred only along small portions of the outflow boundary (confirmed using piezometers). The intermittent stream outflow to Lake Bangazi was also assumed to be negligible.

Rainfall

Rainfall was measured at 15 sites distributed over the full extent of Mfabeni Mire and the surrounding eastern and western dune areas, using a combination of tipping bucket raingauges (TE525, Texas Electronics Inc., Dallas, Texas, USA) and manual raingauges (read weekly) installed with orifice height 1.2 m above ground level. Rainfall collected by the 13 manual gauges averaged 13 % less than that recorded by the two tipping bucket gauges from May 2008 to April 2009. It was assumed that this was due to evaporation from the manual gauges whose data were, therefore, corrected by comparing with data from co-located automatic raingauges. The rainfall data were interpolated over the period May 2008 to April 2009 to derive a rainfall distribution map with 50 mm isohyet intervals (see Figure 1), and this map was used to calculate an area-weighted rainfall input for the Mfabeni Mire water balance calculation.

Total evaporation

Total evaporation for Mfabeni Mire was modelled using meteorological data. A meteorological station was located near the centre of the mire to provide measurements of air temperature and relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland), net irradiance (NRLite, Kipp and Zonen, Delft, The Netherlands), solar irradiance (LI200X, LI-COR, Lincoln, Nebraska, USA), and wind speed and direction (Model 03002, R.M. Young, Traverse City, Michigan, USA) at 2 m above the ground surface. Soil heat flux was also measured using the method described by Tanner (1960). Two heat flux plates (HFT-3, REBS, Seattle, WA, USA) were buried at 0.08 m depth, parallel thermocouples (Type K) were buried at depths of 0.02 m and 0.06 m to measure the heat stored in the peat above the heat flux plates, and volumetric water content (CS615, Campbell Scientific Inc., Logan, Utah, USA) was determined in the upper 0.06 m of the profile. Appropriate statistical functions were applied to the observations made every 10 s and recorded on a datalogger (CR1000, Campbell Scientific Inc., Logan, Utah, USA) at 5-minute, 60-minute and daily intervals. Vapour pressure deficit (VPD) and reference evaporation were calculated on the datalogger using the methods described by Allen *et al*. (1998).

The two distinct vegetation types (swamp forest and sedge/reed fen) were modelled separately. The swamp forest had a canopy height of approximately 20 m, with understorey trees and ferns around 7 m and 3 m tall, respectively. Leaf area index (LAI) was approximately 3.3 (LAI-2200, LiCor, Lincoln, Nebraska, USA) below the trees and approximately 7.2 below the tree and fern canopies. In contrast, the average height of the sedge/reed fen plant community was approximately 0.4 m and its LAI fluctuated between 0.85 in winter and 1.2 in summer. Clulow *et al*. (2012b) measured *ET* over the sedge/reed fen for a one-year period using a combination of the surface renewal and eddy covariance methods. It was found that the Priestley-Taylor model (Priestley & Taylor 1972) explained 96 % of the variation in *ET* for sedge/reed fen and an α of 1.0, applicable throughout the year, was derived for the Priestley-Taylor model. Therefore, the Priestley-Taylor model was used to estimate the contribution from the sedge/reed fen portion of the Mfabeni Mire (1047 ha) at a daily level.

For the 415 ha swamp forest, *ET* was measured and modelled from October 2009 to September 2010 as detailed in Clulow *et al*. (2015), using a combination of eddy covariance (window periods) and sapflow (long-term) equipment. It was found that the *ET* of the swamp forest was best described using the FAO56 Penman-Monteith reference evaporation model (Allen *et al*. 2006) with monthly crop coefficients for the swamp forest over an annual cycle. Total evaporation was, therefore, calculated using the equation:

$$ET = ET_r \cdot K_c \qquad [2]$$

where, ET_r is reference evaporation (mm) and K_c is the crop factor. The FAO56 Penman-Monteith reference evaporation model was computed at hourly intervals as recommended by Irmak *et al*. (2005) and summed to give daily and monthly values, and the monthly crop factors were applied (Equation 2). Although *ET* was applied to an annual water balance, monthly and daily values are presented for their value in aiding understanding of the water balance study.

Quantifying the absolute accuracy of the *ET* measurements used to derive α and K_c is complex. In both cases the eddy covariance technique, which is the international standard for estimating *ET*, was used during discrete measurement periods that formed the basis for modelling *ET* from the sedge/reed fen and swamp forest plant communities. Although there is much discussion on the accuracy of eddy covariance *ET* estimates and associated energy balance closure problems, this measurement technique is used to assess other methods and is generally considered to be accurate to within 10–20 % (Simmons *et al*. 2007, Castellví *et al*. 2008). The sapflow technique that was used to fill gaps in the intermittent eddy covariance data for the swamp forest site is also a highly regarded method, as is the surface renewal technique that was used to infill the periodic eddy covariance record for the sedge/reed fen (Clulow *et al*. 2012b).

Groundwater inflows and outflows

Groundwater well and multi-level piezometer nests were installed at 43 sample sites (Figure 1), using a truck-mounted hollow-stem auger drill rig in the eastern and western dune cordons adjacent to the mire and by hand in the mire itself. In each case the wells and piezometers were inserted to appropriate depths below ground level, based on the peat or dune stratigraphy; up to 30 m in the sandy uplands, ~11 m in the peat, and 16 m in the clay beneath the peat. The wells and piezometers used in the dune cordons were 0.05 m diameter PVC tubes with slots 1.0 m long, covered with geotextile screening. Those used at the 24 sites located within Mfabeni Mire itself were fabricated in the same way but with 0.2 m longitudinal slots. Drive-point piezometers 0.02 m in diameter (Model 615, Solinst™, Canada, Georgetown, CA) were installed in the sand or clay below the peat. Water levels within all wells and piezometers were monitored manually with an electronic dip-meter at weekly intervals from April 2008 to May 2012. Additionally, hydraulic head was measured continuously in six piezometers along the main transect (Model 3001 Levelogger Gold series, Solinst™, Canada, Georgetown, CA).

Groundwater flow at a point can be measured if the hydraulic conductivity of the material in a homogeneous isotropic region of flow is known (Freeze & Cherry 1979). The different sediments comprising the Mfabeni Mire and related basin are assumed to be isotropic (Rawlins & Kelbe 1991, Taylor *et al*. 2006). Horizontal hydraulic conductivity measurements were carried out infield using the bail test procedure (Hvorslev 1951) with the piezometers and wells described above. Spatial heterogeneity within the mire was incorporated by applying the appropriate hydraulic properties to the different sedimentary units. In the western portion of Mfabeni Mire, groundwater (GW_{in}) flows into the peat body from two sand layers; and on the eastern boundary, the outflow of groundwater (GW_{out}) is from the peat body (incorporating four peat and two sand layers) into the adjacent sand body (Figure 4). Discharge was calculated across the regions of inflow and outflow through a cross-sectional area of depth *h* using Darcy's law for saturated flow:

$$Q = -K\left(\frac{dh}{dl}\right)A \qquad [3]$$

where Q is discharge (m^3 s^{-1}); K is hydraulic conductivity (m s^{-1}); dh/dl is the hydraulic gradient (calculated at the western inflow and eastern outflow boundaries) and A is the cross-sectional area (m^2). The flow per unit width of the main transect was calculated, then extrapolated across the lengths of the different lithological units (Table 1) of the western (groundwater inflow boundary) and eastern (groundwater outflow boundary) edges of the mire to determine the system's groundwater flux.

Stream outflow

The efflux from Mfabeni Mire into Lake St Lucia was measured at a compound V-notch weir beneath the Nkazana Bridge (sample point 'e' in Figure 1). The stage height of the water in the weir was measured every 15 minutes (Model 3001 Levelogger Gold

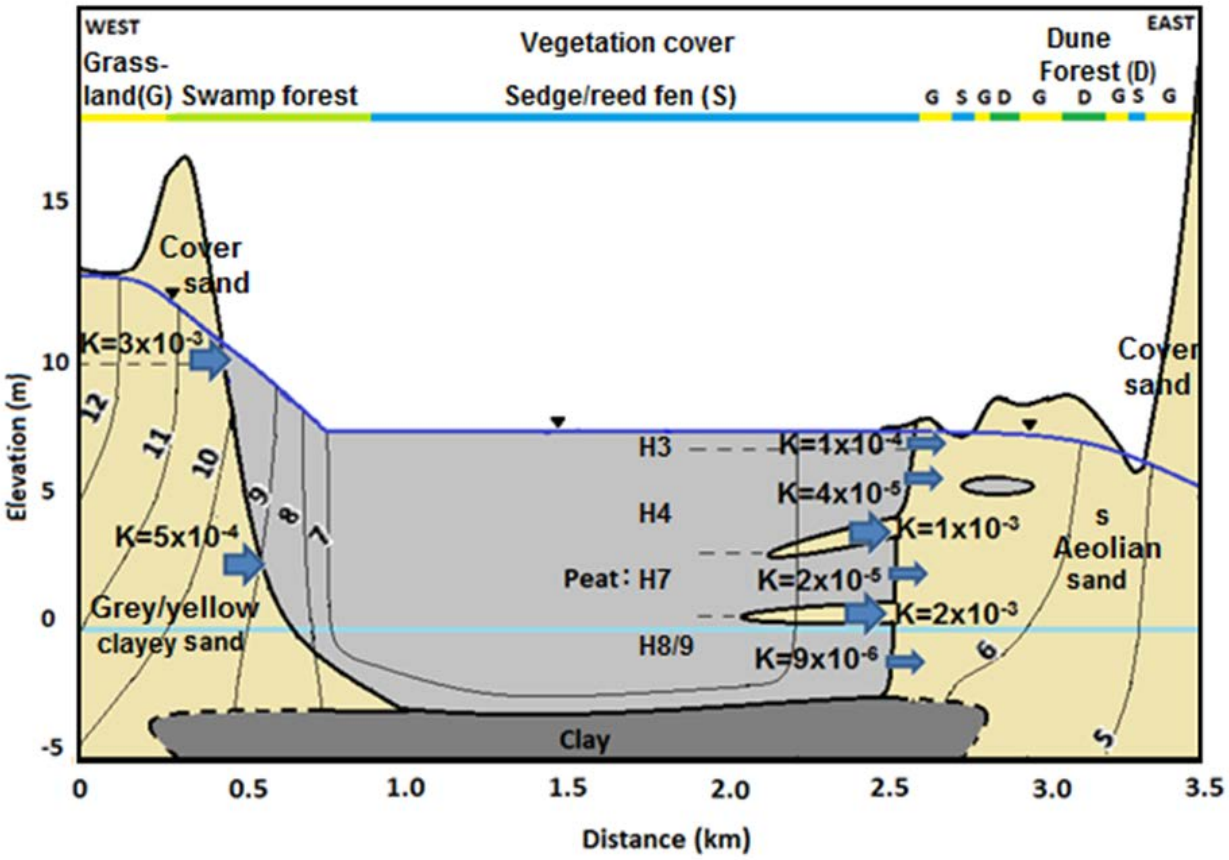

Figure 4. Schematic diagram of groundwater flow (simplified) through Mfabeni Mire, with hydraulic conductivity values shown in m s^{-1}. The large blue arrows indicate flow through sand, and the smaller blue arrows indicate flow through peat.

Table 1. Lithological units, dimensions and hydraulic conductivity values used in the groundwater flow calculations for Mfabeni Mire.

	Lithological Unit	*K* (m s^{-1})	Length (m)	Thickness (m)
Western edge	Cover sand	3.08E-05	8500	2.5
	Grey/yellow sand and silt with clay	5.05E-06	8500	13
Eastern edge	Peat (H3)*	9.89E-07	8500	0.5
	Peat (H4)	3.80E-07	7480	2.5
	Sand	1.19E-05	2380	0.6
	Peat (H7)	2.01E-07	6040	2.4
	Sand	2.29E-05	2380	0.6
	Peat (H8/9)	1.09E-07	3230	3.4

*H values refer to the level of humification based on the von Post humification scale (von Post 1922), which ranges from H1 (completely undecomposed peat) to H10 (highly decomposed peat).

series, Solinst™, Ontario, Canada). A calibrated Kindsvater-Carter equation was applied to determine the discharge of the Nkazana Stream (Grundling 2014) from May 2008 to mid-February 2009. The discharge from mid-February 2009 to April 2009 was inferred from an adjacent measuring weir in the Mphate catchment operated by the Department of Water Affairs as described by Grundling (2014).

Change in storage

Water storage change (ΔV) within Mfabeni Mire was determined from May 2008 to April 2009 on the basis of water table fluctuations at nine individual sites across the peatland (five in the sedge/reed fen and four in the swamp forest). Perforated PVC access tubes, lined with geotextile, were installed at selected groundwater level monitoring sites (Solinst 101P2 water level meter, Ontario, Canada).

Specific yield values for the different peatland types were determined from monoliths (0.1 m cubes) of peat collected at each site. These were initially immersed in water for eight hours. Excess water was then removed, the samples weighed, and the peat allowed to drain under gravity until dripping stopped before re-weighing. Specific yield was determined by:

$$S_y = \frac{V_{wd}}{V_T} \qquad [4]$$

where, V_{wd} is the volume of water (mm^3) drained and V_T is the total volume of the monolith (mm^3).

The change in water table level (Δh) over the annual water balance period was measured at each site and combined with the S_y to calculate ΔV using:

$$\Delta V = S_y \cdot \Delta h \qquad [5]$$

The final ΔV was calculated by area weighting the results from the sedge/reed fen and swamp forest.

RESULTS

Rainfall

Rainfall at the meteorological station on Mfabeni Mire exhibited the seasonality and variability described in previous studies of the area (Taylor *et al*. 2006). The highest daily rainfall was 93 mm on 27 January 2009, while on five different occasions the daily rainfall was approximately 50 mm. Monthly rainfall (Figure 5) was highest in January 2009 (250 mm) and lowest in July 2008 (4 mm). Although the area is described as a summer (October to March) rainfall region, there was a noticeable delay in the onset of summer rainfall in 2008, with relatively low rainfall totals of 21 mm, 87 mm and 48 mm in October, November and December, respectively.

Rainfall measured at the network of 15 raingauges within and around Mfabeni Mire indicated some spatial variability (up to 10 %) over the year May 2008 to April 2009 (Figure 1). Rainfall was higher in the northern part of the mire (1050–1100 mm) than in its southern part (1000–1050 mm). The annual area-weighted rainfall derived for the water balance calculation was 1,031 mm.

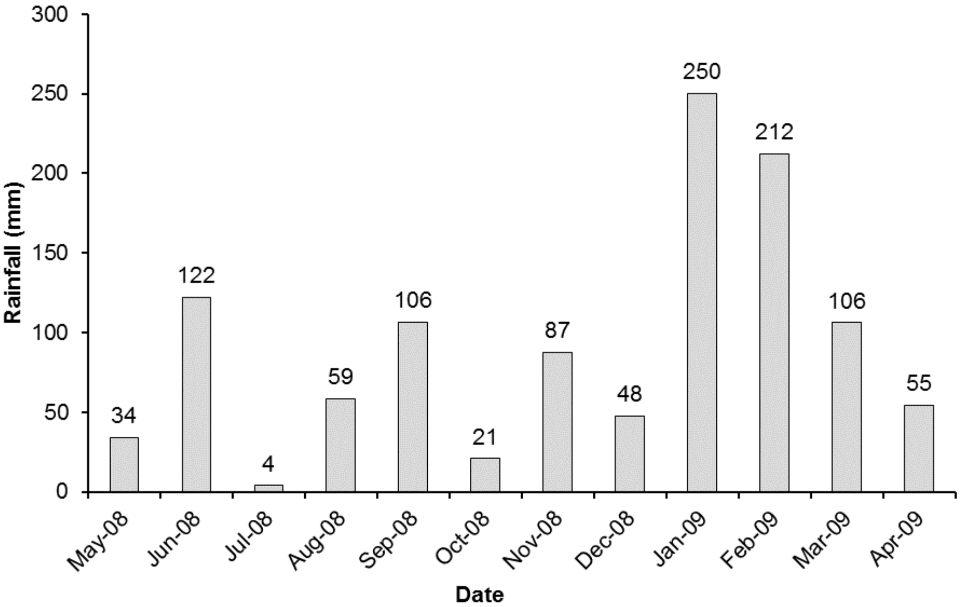

Figure 5. Monthly rainfall from May 2008 to April 2009, measured at the meteorological station on Mfabeni Mire using an automatic raingauge.

Total evaporation

The pattern of daily *ET* was seasonal for both sedge/reed fen and swamp forest; however, the annual pattern of daily *ET* differed between the two plant communities (Figure 6). For sedge/reed fen, the daily *ET* on clear days followed a smooth sinusoidal curve; whereas the swamp forest *ET* was more variable, with daily *ET* taking longer to peak within the summer season and high rates being maintained into the autumn period. Reed/sedge fen and swamp forest present significantly different canopies, and Clulow *et al*. (2015) attribute the differences in *ET* in part to a build-up of heat energy within the swamp forest, which governs physiological processes, as well as to the different canopy architectures.

The peak summer rates of daily *ET* were 6 mm and 8 mm from the sedge/reed fen and swamp forest, respectively. The winter maximum daily *ET* of approximately 2 mm was significantly lower than the summer *ET* at both sites. The occurrence of cloud cover was evident, particularly over the summer period (October to March), from the numerous days on which *ET* was reduced or below the higher rates of previous and following days.

ET accumulated to monthly values exhibited a typical seasonal pattern (Figure 7). The summer monthly *ET* (October to March) ranged from 94 mm in November 2008 to 126 mm in January 2009. The winter monthly *ET* (April to September) ranged from 46 mm in June 2008 to 85 mm in September 2008.

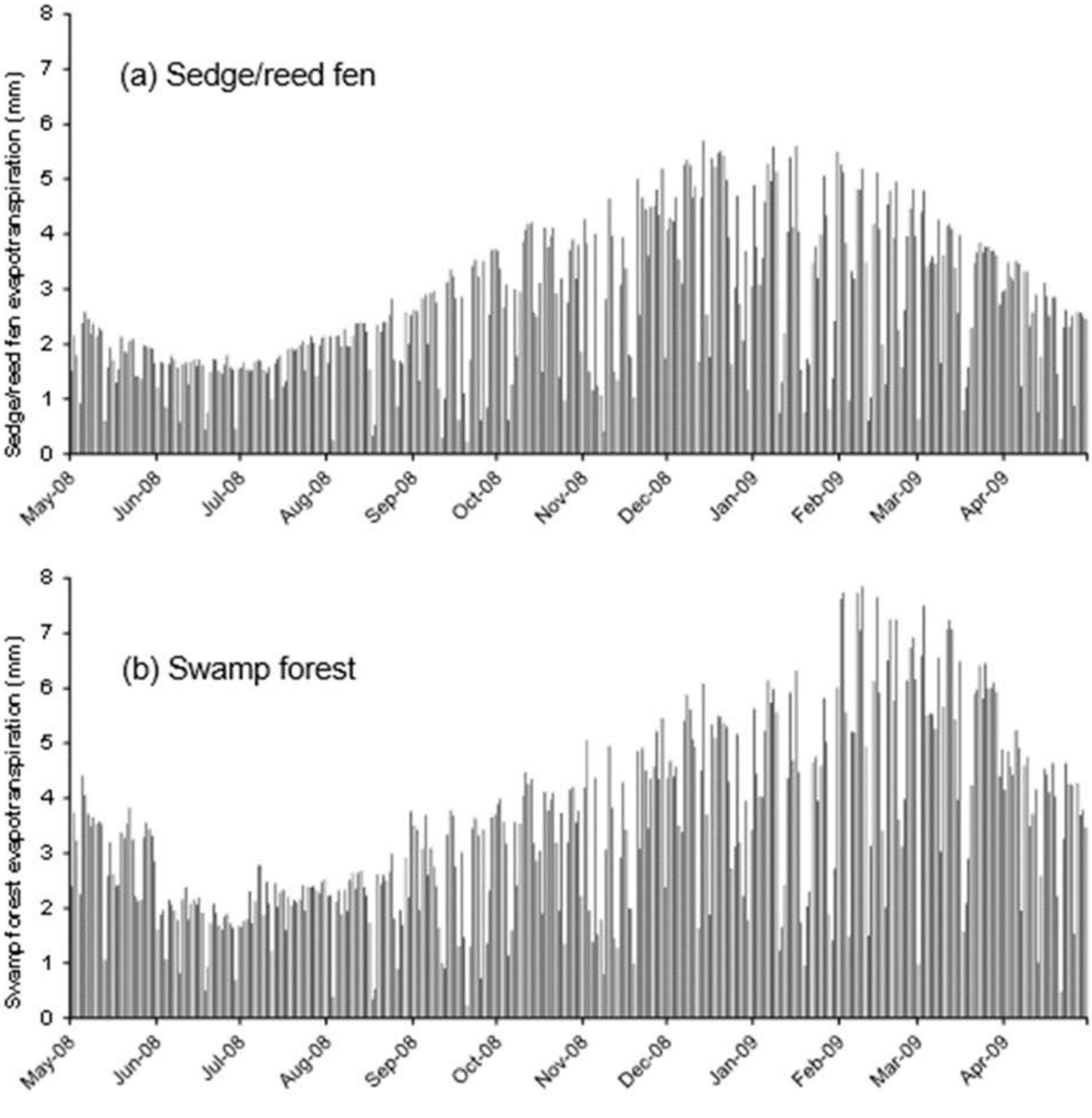

Figure 6. Total daily evaporation modelled for (a) sedge/reed fen and (b) swamp forest.

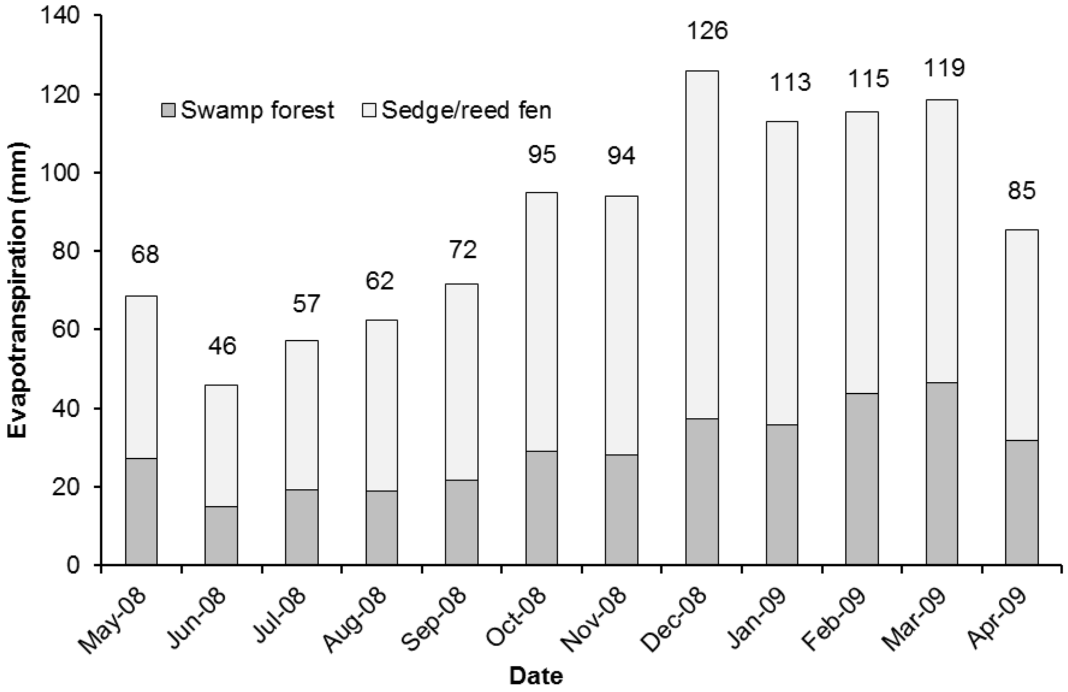

Figure 7. Total evaporation modelled for Mfabeni Mire from May 2008 to April 2009 by area weighting the contribution to total evaporation from the swamp forest and sedge/reed fen plant communities.

There was a clearly discernible difference between winter and summer *ET*. Annual *ET* from the swamp forest was 28 % higher than from the sedge/reed fen. The swamp forest (28 % of the mire surface area) contributed 34 % (354 mm) of the mire *ET* whilst the sedge/reed fen (72 % of the mire surface area) contributed only 66 % (699 mm).

Groundwater inflows and outflows

Groundwater flows through the peat body of Mfabeni Mire from west to east. Based on the simplified geology described by P. Grundling *et al*. (2013) and hydrological characteristics described by Grundling (2014), the groundwater flows into and out of the mire along its western and eastern edges, respectively. The flows determined at geological boundaries on the main transect were assumed to represent the flows along the whole of the respective mire edges due to the consistent geological profile found to run parallel to the coastline by Taylor *et al*. (2006). An annual GW_{in} of 2.01 × 10^5 m^3 yr^{-1} (14 mm yr^{-1}) was calculated at the western edge of the peatland, and a GW_{out} of 4.13 × 10^3 m^3 yr^{-1} (0.3 mm yr^{-1}) at the eastern edge (Table 2).

Changes in storage

The change in water level in the sedge/reed fen plant community over the 12-month period (May 2008 to April 2009) ranged from 0.01 m to 0.1 m in the northern part of the sedge/reed fen area (Sites 2 and 3) to -0.03 m in the central fen and -0.07 m in the southern fen area (Table 3). Water level changes in the swamp forest over the same period ranged from 0.04 m to 0.12 m in sloping areas to 0.06 m in the lowest-lying swamp forest area (Table 3). These results were used together with average specific yield values of 0.19 (n = 25, standard deviation = 0.062) for sedge peat and 0.15 (n = 8, standard deviation = 0.055) for swamp forest peat to estimate net ΔV (Equation 5), which amounted to -3 mm (-41,484 m^3) for Mfabeni Mire as a whole (Table 4).

Streamflow

Monthly streamflow from Mfabeni Mire into Lake St Lucia *via* the Nkazana Stream ranged from a minimum of 0.1 mm (1,063 m^3 $month^{-1}$) in the dry season (August 2008) to a maximum of 2.1 mm (30,573 m^3 $month^{-1}$) in the wet season (March 2009). The unseasonably high flow rate of 1.4 mm $month^{-1}$ (20,468 m^3 $month^{-1}$) in June 2008 (dry season) and the low flow rate of 0.02 mm $month^{-1}$ (227 m^3 $month^{-1}$) in December 2008 (wet season) are noticeable (Figure 8), but these values are consistent with the rainfall measured during these months (Figure 5). The annual streamflow was 9 mm (131,916 m^3 distributed over the 1,462 ha area of the mire).

Table 2. Inputs to the Darcy equation (Equation 3) and the final annual groundwater inflow and outflow at the western and eastern boundaries of Mfabeni Mire, based on an area of 1,462 ha.

	Flow Unit	K(m s^{-1})	dh/dl (i)	Length (m)	Thickness (m)	A (m^2)	Q=-KiA (m^3 yr^{-1})
Western boundary	Sand	3.08E-05	4.17E-03	8.50E+03	2.5	2.13E+04	86,000
	Sand & Silt	5.05E-06	6.56E-03	8.50E+03	13	1.11E+05	115,000
	Annual groundwater inflow (m^3)						201,000
	Annual groundwater inflow (mm)						14
Eastern boundary	Peat	9.89E-07	2.00E-03	8.50E+03	0.5	4.25E+03	2.65E+02
	Peat	3.80E-07	2.00E-03	7.48E+03	2.5	1.86E+04	4.46E+02
	Sand	1.19E-05	2.00E-03	2.38E+03	0.6	1.44E+03	1.08E+03
	Peat	2.01E-07	2.00E-03	6.04E+03	2.4	1.44E+04	1.82E+02
	Sand	2.29E-05	2.00E-03	2.38E+03	0.6	1.44E+03	2.08E+03
	Peat	1.09E-07	2.00E-03	3.23E+03	3.4	1.09E+04	7.47E+01
	Annual groundwater outflow (m^3)						4,130
	Annual groundwater outflow (mm)						0.3

Table 3. Water table depth below surface (m) on 02 May 2008 and 30 April 2009 for the sedge/reed fen and swamp forest areas.

	Sedge/reed fen sites					Swamp forest sites			
	2	3	6	7	10	a	b	c	d
02 May 2008	0.73	0.57	0.34	0.52	0.66	0.53	0.82	0.61	0.74
30 Apr 2009	0.63	0.56	0.41	0.55	0.73	0.58	0.76	0.73	0.78
Change in water level (m)	0.10	0.01	-0.07	-0.03	-0.07	-0.05	0.06	-0.12	-0.04

Table 4. Calculation of storage change for Mfabeni Mire from 02 May 2008 to 30 April 2009.

	Average change in water level (m)	Specific yield	Area (ha)	Storage change (m^3)	Storage change (m)
Sedge/reed fen	-0.010	0.19	1,047	-19,370	-0.002
Swamp forest	-0.036	0.15	415	-22,114	-0.005
Total			1,462	-41,484	-0.003

Water balance

The annual water balance (Equation 1) was determined using measured or modelled values for all components, and the equation rearranged to determine the error term (ŋ). Total evaporation (1,053 mm) and rainfall (1,031 mm) dominated the water balance (Figure 9), followed by GW_{in} (14 mm), S_{out} (9 mm) and ΔV (-3 mm), and the smallest flux was GW_{out} (0.3 mm). The negative sign of ΔV indicates a net loss in storage between May 2008 and April 2009). After resolving all components of the Mfabeni Mire water balance, the error, ŋ, was -15 mm. This deficit is only 1.9 % of *ET* and considered good closure of the water balance.

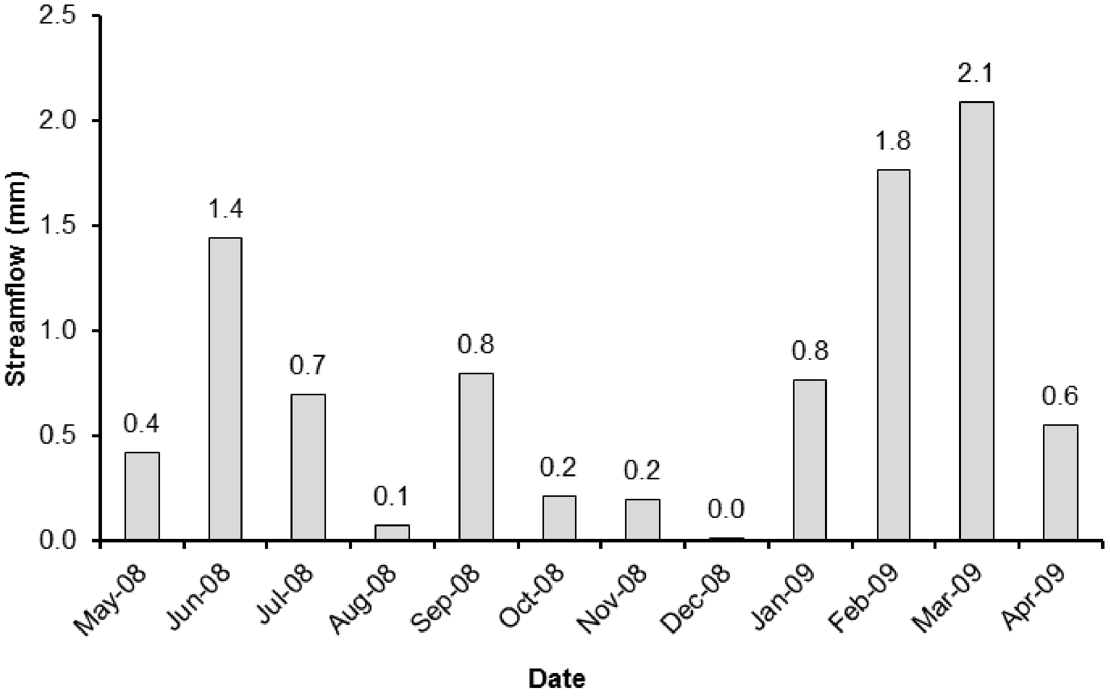

Figure 8. Monthly flow in the Nkazana Stream from May 2008 to April 2009.

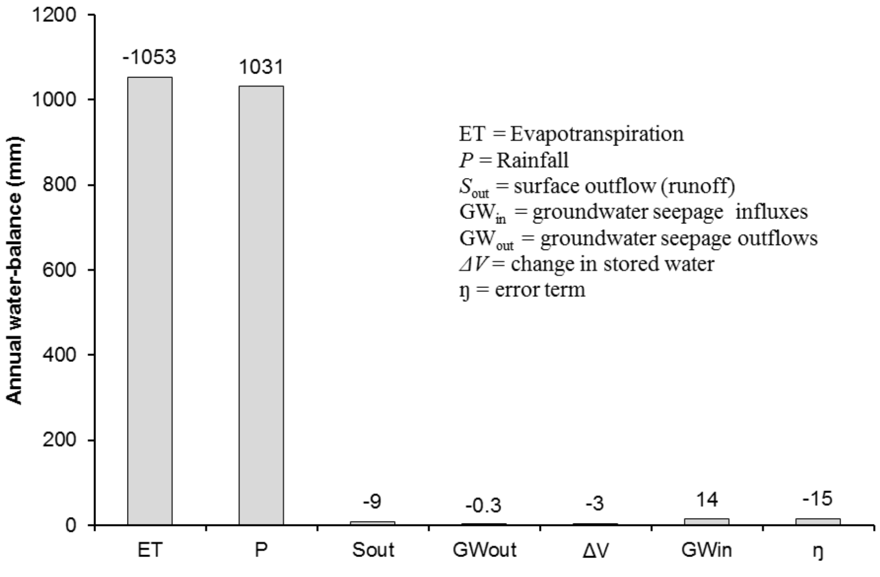

Figure 9. Water balance of the Mfabeni Mire from May 2008 to April 2009.

DISCUSSION

The annual rainfall for Mfabeni Mire was determined from May 2008 to April 2009 and was 14 % below the long-term annual average of 1,364 mm yr^{-1} (1961–1989) at the coast (Wejden 2003). The rainfall measured in the study year followed a seasonal trend of wetter summer months in contrast to drier winter months. However, the dry period persisted into the summer months of October, November and December 2008, supporting the report of highly variable rainfall in the area by Taylor *et al*. (2006). These authors indicated that a strong rainfall gradient persisted from east to west across the Eastern Shores. The fifteen raingauges in the current study covered a relatively small area measuring 6 km east–west and 10 km north–south, and operated for only one year, so could not be used to test this previous finding. However, the annual rainfall recorded at different rainfall stations varied by up to 10 %, with higher rainfall occurring towards the northern central area of the mire. The western dunes, with grassland and relatively extensive bare soil areas (which are the recharge areas for Mfabeni Mire groundwater), received approximately 50 mm yr^{-1} more rainfall than the eastern dune area which is covered in dune forest vegetation that is opportunistic in its water use, quickly utilising available water (Clulow *et al*. 2013), and contributes no GW_{in} to the Mfabeni Mire.

Total evaporation was the largest component of the Mfabeni Mire water balance and exceeded rainfall during the period of monitoring by 22 mm (2.1 % of the incident rainfall). Evaporation rates were higher for swamp forest than for sedge/reed fen. Therefore, a change in the relative areas of swamp forest and sedge/reed fen within the mire would alter the fine balance between ET and P, impacting on the resulting stream and groundwater flows. In addition, the suppression of ET at Mfabeni Mire due to cloud cover and low vapour pressure deficit are important controls that help maintain an equilibrium between the dominant components of the water balance (ET and P). Any shift in these controls (e.g. due to climate change) could disturb the water balance of the mire, and the resulting higher or lower water table in the western dune mound cause expansion or contraction, respectively, of the swamp forest.

For both swamp forest and sedge/reed fen, the difference between summer and winter ET was driven primarily by the seasonal change in solar irradiance by virtue of the proximity of the water table to the mire surface (Table 3). The noticeable difference in seasonal patterns of daily ET between these two plant communities could be a result of the high and variable wind speeds recorded in the area (Clulow *et al*. 2012b), which were used to model ET from the swamp forest (FAO56 Penman-Monteith model) but not from the sedge/reed fen (Priestley-Taylor model). The early summer increase in ET from the swamp forest was delayed, but then increased rapidly in February 2009. The delay was ascribed by Clulow *et al*. (2015) to an increase in the monthly average vapour pressure deficit from approximately 0.7 kPa in January to 1.0 kPa in February. Such changes in vapour pressure deficit are certain to influence ET from the swamp forest, where humid conditions are a limiting factor for tree transpiration. Leaf area index was much higher below the canopy of the swamp forest (7.2) than in the sedge/reed fen (0.85–1.2), providing a much greater leaf surface area for transpiration (Clulow *et al*. 2013). Also, the high wind speeds shown to be dominant in the area are likely to have contributed to higher ET rates for the swamp forest than for the fen because the higher surface roughness of the swamp forest canopy contributes to greater turbulence and atmospheric mixing, and hence greater ET as a result of warm, dry air being drawn down through the convective boundary layer and removing saturated air from above the canopy (Lhomme 1997).

The hydrological study in Grundling (2014) showed that the water table descends abruptly at the eastern edge of Mfabeni Mire. This is likely to be a result of the absence of highly humified peat and an impeding basal clay layer beyond this point (P. Grundling *et al*. 2013), and also the relatively permeable sediments through which flow occurs. Consequently, the eastern dunes do not contribute groundwater inflow to the water balance of the mire, contrary to previous suggestions from Rawlins (1991) and Taylor *et al*. (2006). Groundwater inflow is mainly from the western dunes unless flood events such as the Demoina tropical cyclone of 1984 occur. Most of the time, groundwater inflow from the western dunes contributes a relatively small proportion of the water budget (< 2 % of rainfall) but is, nonetheless, likely to be an important factor in sustaining waterlogging and anaerobic conditions during dry periods that has aided in peatland development and currently assists in maintaining the integrity of the mire system (c.f. Lapen *et al*. 2005). Groundwater outflow from Mfabeni Mire (-0.3 mm) is insignificant compared to the other water balance components. It is, therefore, doubtful that groundwater outflows from Mfabeni Mire contribute significantly to adjacent ecosystems such as Lake Bangazi and the smaller eastern wetlands.

Surface inflow to the Mfabeni Mire does not occur because the catchment's geology is dominated by highly permeable sands, resulting in high infiltration rates and minimal surface runoff (Rawlins 1991). The annual outflow through the Nkazana Stream is more than two orders of magnitude less than the long-term annual average *P*, underlining the importance of *ET* losses from the system. Sustained groundwater discharge from the western dunes regulates baseflow in the Nkazana Stream, which drains southward to Lake St Lucia. Consequently the Nkazana Stream is perennial, although it is characterised by persistently low flows during the dry season. However, this relatively low surface flow is locally significant during dry periods, providing freshwater refugia as it enters Lake St Lucia (Taylor *et al*. 2006).

Van Seters & Price (2001) concluded that, in an error assessment of a peatland water balance, the different components should be assessed in relative terms as there is no absolute standard for evaluation of errors. Rainfall recorded at the 13 manual gauges averaged 13 % less than that logged at the two tipping bucket raingauges from May 2008 to April 2009. The difference is likely to arise from evaporation of part of the catch of a manual gauge between weekly readings; the data were corrected accordingly. The (TE525) tipping bucket raingauges have an error range of 1 % up to 25 mm h^{-1} (Riddell 2011). Winter (1981) found that short-term average precipitation estimates are typically within 15–30 % of true values but annual estimates can be better, deviating from true values by about 5 %. Given the dominance of precipitation in the Mfabeni Mire water balance, the potential error is larger than the annual inputs and losses from all other sources except *ET*.

Modelled estimates of *ET* using the Priestley Taylor and FAO56 Penman-Monteith models rely on finding the most suitable estimates of α and K_c, respectively, from similar vegetation types and locations. This study benefited by having values of α and K_c for both dominant plant communities derived from actual measurements using eddy covariance, surface renewal and sapflow techniques. In addition, we were able to model *ET* from the same weather station site and the same instruments that were used to derive α and K_c; and the models were applied, as intended, over relatively homogeneous areas where the vegetation was not water-limited at any stage. While many water balance studies derive *ET* as a residual term in the water balance, in this study *ET* was resolutely derived as accurately and precisely as possible because of the acknowledged importance of *ET* in this environment.

The groundwater inflow and outflow calculations used in the water balance are a function of the hydraulic characteristics (*K*) of the substrata adjacent to and within the peatland and their overall extent (area and thickness). The hydraulic characteristics were determined along the main transect and then extrapolated to the whole mire. Surveyed altitudes could have vertical errors of 20–50 mm. Whereas the peat was investigated along seven transects with 100–200 m sampling intervals, only three sites on the adjacent sand dunes at either margin were studied. Therefore, the expected error could be as much as 30–50 %. However, given the small values of groundwater inflow and loss, relatively large percentage inaccuracies will result in very small errors in estimation of the absolute values of groundwater fluxes. The estimate of water storage change is a function of both the hydraulic character (S_y) of the peat and water table measurements. The latter were made broadly across the system to provide a representative value. Furthermore, as storage change is not a cumulative measurement, errors are likely to cancel one other over a period of one year. Also, the total change in storage is relatively small.

In estimating streamflow, the V-notch portion of the compound weir was accurately calibrated and captured low-flow conditions well. Extremely low flows of 5 $m^3 h^{-1}$ were measured for 35 % of the time. Higher flows raising the stage into the square-section part of the weir were more difficult to calibrate accurately, and so have greater uncertainty. There were several high flow measurements exceeding 250 $m^3 h^{-1}$, but high flows occurred for less than 10 % of the time. Due to data loss from mid-February to 01 May 2009, discharge was inferred for the Nkazana Stream. The discharge patterns at the weir on the Mpate Stream, 15 km to the south-west, were similar to those at the Nkazana Weir (coefficient of determination = 0.77). The period of inferred discharge represents 20 % of the monitoring period. Our estimate of average flow in the Nkazana Stream (15 $m^3 h^{-1}$ from May 2008 to April 2009) compares well with a previous estimate of 10 $m^3 h^{-1}$ (no period provided) by Kelbe *et al*. (2004), but is less than the 50 $m^3 h^{-1}$ determined for a limited period of time (June 1989 to August 1989) by Rawlins (1991). Given the relatively small value of the streamflow component of the water balance, the uncertainty again results in a small absolute error.

The small residual term (-15 mm) provides good closure of the water balance, but does not necessarily reflect the errors in individual components or the larger possible errors discussed above. Errors in the large components, namely *P* and *ET*, could cancel one another, and there is no way to be certain whether this occurred. However, considering the potential errors, the water balance clearly illustrates the relative magnitudes of its individual components. The water balance of Mfabeni Mire is dominated by, and thus most sensitive to, *P* and *ET*; although the similar magnitudes of these two components make the other water balance fluxes highly important to the functioning of the system.

In identifying major threats to the equilibrium of the Mfabeni Mire water balance, factors influencing ET and P are clearly of highest priority. The most likely cause of change in ET would be a change in land use or climate. The Eastern Shores of the iSimangaliso Park have been managed since the 1950s on a dual basis as a conservation area with commercial timber interests. Timber operations focused on planting *Pinus* species, exotic to southern Africa and often invasive, therefore resulting in lower groundwater levels with detrimental impacts on adjacent lakes and wetlands (Rawlins & Kelbe 1991, Taylor *et al*. 2006). Furthermore, planting of *Pinus* and *Casuarina* species to stabilise active dunes in the western part of the Mfabeni Mire catchment reduced recharge of the aquifer by rainwater. Management interventions such as removing these plantations and other invasive species since 2000 (Været *et al*. 2009) were a significant step in protecting the groundwater resource that is crucial to ecosystem support by reducing ET. Active dune-forming processes should be encouraged in the groundwater recharge areas of the western dunes to stimulate recharge of the aquifer (Stuyfzand 1993). This could be achieved by clearing invasive species, which reduce available groundwater not only by intercepting rainfall, but also because they transpire more rapidly than dry grasslands. In Clulow *et al*. (2012b) it was shown that the accumulated ET of dry grassland on the western dunes was 478 mm over a year; whereas, over the same period, the accumulated ET of the sedge/reed fen was 900 mm and that of the swamp forest was 1,125 mm. The role of the western dunes in supplying groundwater, and the effect of their vegetation in apportioning available water between ET and GW_{in}, should be considered critical to the functioning of Mfabeni Mire. Similarly, any expansion of the swamp forest plant community into the Mfabeni Mire would increase the overall ET from the mire and should be monitored and fully understood in terms of vegetation succession.

Climate change could impact both ET and P. Taylor *et al*. (2006) state that the impact of climate change in this century is likely to be minor compared to the anthropic influences of the last century. However, the controls of cloud cover and low vapour pressure could potentially be nullified by climate change, leading to a deficit in the water balance of Mfabeni Mire with lowering of the water table followed by drying and burning of the peat. Climate change predictions are complex, but it has been accepted by most experts that climate change will bring an increase in the frequency of extreme events (Mason *et al*. 1999). The area is already prone to extended droughts. More frequent and intense droughts are likely to increase episodic hypersaline events and desiccation of the lake, reduce recovery time between events, and thus cause gradual degradation and irreversible loss of biodiversity (Chrystal 2013). The stabilising effect of the Mfabeni Mire becomes most critical during these periods.

CONCLUSIONS

Determining and quantifying the contributions of different components of the water balance enhances our understanding of how wetland systems function in various climates and their ability to survive climatic instability. Knowledge of the water balance also improves our understanding of its components and how the wetland contributes to and interacts with the surrounding areas.

Although the water balance of Mfabeni Mire was dominated by ET and P, the wetland still contributed efflux to downstream ecosystems (by streamflow) and, to a lesser extent, to adjacent ecosystems (by groundwater outflow). The mire functions primarily as a regulator of the regional water table, thereby maintaining high groundwater levels and wetness of the accumulated peat within the mire. Its value in a wider landscape where seasonal change and longer-term dry periods are major ecological drivers lies in its role in damping the effects of climatic variation. The Mfabeni Mire does this by stabilising groundwater conditions, and thus the environments of adjacent ecosystems. Consequently, peatlands in arid climates should be recognised as assets in natural resource management, and their potential to support adjacent ecosystems should be protected through appropriate planning and conservation practices.

There have been few water balance studies in South Africa where all terms of the water balance were measured. Everson *et al*. (1998) studied a montane grassland catchment in the Drakensberg mountains of South Africa and found that P was equally split between streamflow and ET, with ET approximately 54 % of P over the long term. Clulow *et al*. (2014) quantified the water balance of an inland afforested catchment where all terms were measured, and found ET to exceed P over a period of eight years. Both of these studies were undertaken in climatic and geological settings that differ from those of the Mfabeni Mire. Therefore, the wetland water balance provided here is an important contribution to the knowledge base for South Africa, and especially to our understanding of coastal peatlands.

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