Surface oscillation in peatlands: How variable and important is it?

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Abstract

Hydrology, particularly the water table position below the surface, is an important control on biogeochemical and ecological processes in peatlands. The position of the water table is a function of total storage changes, drainable porosity and peatland surface oscillation (PSO). Because the absolute level of the peat surface (ASL) oscillates in a peatland, we can assign two different water table positions: the water table depth below the surface (relative water level, RWL) and the water table position above an absolute elevation datum eg. sea level (absolute water level, AWL).

A review of 37 studies that report peatland surface oscillation indicate a wide range (0.4-55 cm), which is to the same order as (or one order smaller than) water storage changes and RWL fluctuations. PSO can vary substantially across a single peatland and through time. A set of mechanisms (flotation, compression/shrinkage, gas volume changes and freezing) is hypothesised to cause ASL changes. The potential of PSO to reduce RWL fluctuations trended (mean in %) floating peatlands (63) > bogs (21), fens (18) > disturbed peatlands (10) with respect to peatland types.

To investigate the spatiotemporal variability of peatland surface oscillation, AWL and ASL were monitored continuously over a one-year period (one site) and monthly (23 sites) in a warm-temperate peatland that is dominated by *Empodisma minus* (Restionaceae). A new measurement method was developed by pairing two water level transducers, one attached to a stable benchmark (→AWL) and one attached to the peat surface (→RWL).

From August 2005 until August 2006 the ASL oscillated at one site through a range of 22 cm following AWL fluctuations (in total 47 cm). Consequently, RWL fluctuations were reduced on average to 53% of AWL fluctuations. The strong AWL-ASL relationship was linear for 15 sites with manual measurements. However, eight sites showed significantly higher rates of peatland surface oscillation during the wet season (ie. high AWLs) and thus a non-linear behaviour. Temporary flotation of upper peat layers during the wet season may have caused this non-linear behaviour. On the peatland scale AWL fluctuations (mean 40 cm among sites) were reduced by 30–50% by PSO except for three sites with shallow and dense peat at the peatland margin (7–11%). The reduction of RWL fluctuation was high compared to literature values. The spatial variability of PSO seemed to match well with vegetation patterns rather than peat thickness or bulk density. Sites with large PSO showed high cover of *Empodisma minus*.

Surface level changes exhibited surprisingly hysteretic behaviour subsequent to raised AWLs, when the rise of ASL was delayed. This delay reversed the positive ASL-AWL relationship because the surface slowly rose even though AWL started receding. Hysteresis was more pronounced during the dry season than during the wet season. The observed hysteresis can be sufficiently simulated by a simplistic model incorporating delayed ASL fluctuations.

PSO has wide implications for peatland hydrology by reducing RWL fluctuations, which feed back to peat decomposition and plant cover and potentially to (drainable) porosity. Stable RWL also reduce the probability of surface run-off. It is further argued that the gas content of the roots of plants, particularly *Empodisma minus*, added enough buoyancy to detach the uppermost peat layers resulting in flotation.

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1 Introduction

1.1 The importance of the water table position for processes in peatlands

Water creates conditions that distinguish wetlands from terrestrial ecosystems. Water slows the decomposition of organic matter down and peat forming ecosystems, ie. mires, are usually associated with water tables close to the surface. Water table dynamics in mires are minor when compared to terrestrial and river ecosystems (Joosten and Clarke, 2002; van der Schaaf, 1999). Various factors can reduce water table fluctuations: reduced evaporation (eg. Campbell and Williamson, 1997; Ingram, 1983; Lafleur et al., 2005), reduced subsurface and surface run-off (eg. Couwenberg and Joosten, 1999; Ivanov, 1981; van der Schaaf, 1999), increased input of groundwater and surface water (eg. Glaser et al., 1997; Glaser et al., 1981; Koerselman, 1989; Racine and Walters, 1994) and a large drainable porosity (Ingram, 1983). The seasonal oscillation of the surface level also affects water table fluctuations. The potential of peatland surface oscillation in reducing water table dynamics (cf. Kulczynski, 1949) is more and more accepted (Kennedy and Price, 2005; Roulet, 1991; Roulet et al., 1991).

Generally, water table and water chemistry dynamics, vegetation dynamics and peat formation/ decomposition are mutually dependent in mires. Peat formation in particular is vital for carbon and nutrient sequestration and transformation and formation of a highly porous substrate. A stable water table just below the surface maximises peat formation (Bauer 2004; Belyea and Clymo, 2001; Blodau, 2002). Similarly, biogeochemical processes are controlled by the water table position. Water tables close to the surface (-10 to 10 cm below the surface) may reduce CO_2 emission but can increase CH_4 emissions and vice versa for water tables well below the surface (eg. 30 cm) (reviewed in Blodau, 2002). Water tables just below the surface result in large subsurface run-off (Ivanov, 1981; Koerselman, 1989; Surridge *et al.*, 2005), which can decrease sharply with depth given a steep vertical gradient of permeability often found in mires (Baumann, 2006; Hoag and Price, 1995; Ivanov, 1981). However water tables above the surface promote overland flow (cf. surface run-off) that exceed rates of subsurface run-off (Hemond, 1980; van der Schaaf, 1999).

Peatlands host many species valuable for nature conservation (Clarkson, 2002; Joosten and Clarke, 2002) and species composition can feed back to biogeochemical cycles (Bubier *et al.*, 2003; Keppler *et al.*, 2006; Saarnio *et al.*, 1997; Strack *et al.*, 2006). The distribution of plant species (in peatlands) is strongly controlled by the mean position and fluctuations of the water table below the surface (eg. Clymo and Hayward, 1982; Ivanov, 1981; Kotowski et al., 1998; Wheeler and Shaw, 1995; Wierda et al., 1997), nutrient availability (Clarkson *et al.*, 2004; Venterink *et al.*, 2002; Wassen *et al.*, 2005) and alkalinity (Glaser et al., 1981; Sjors and Gunnarsson, 2002).

One may wonder how the water table can be related to all these processes. In fact, the water table position below the surface sets the thickness of the unsaturated zone including its moisture content (Barber et al., 2004; Heikurainen et al., 1964; Schlotzhauer and Price, 1999). The soil moisture content controls aeration and redox processes and thus soil chemistry (Barber et al., 2004; de Mars and Wassen, 1999). Under water logged conditions oxygen is unavailable and the redox potential is low favouring the formation of phytotoxins (Crawford, 1983; Mainiero, 2006). So high water tables cause plant stress but can reduce decomposition rates leading to peat formation. Conclusively, the water table position below the surface can serve as a surrogate for measurements of redox and moisture state of soils in peatlands and is therefore the focus of green house gas and ecological studies.

1.2 Controls of the water table position

The position of the water table is a function of total storage changes, drainable porosity and surface elevation changes. The vast majority of hydrological studies in peatlands have only focused on storage changes and drainable porosity while neglecting the importance of an oscillating surface. In brief, storage changes result from an imbalance between water input (ie. precipitation, groundwater and surface water) and output (evaporation, groundwater recharge, lateral run off and surface run off), in a magnitude of centimetres (Holden, 2005; Ingram, 1983). Storage changes in unconfined aquifers translate into hydraulic head changes, as defined by Freeze and Cherry (1979), proportional to the drainable porosity. Drainable porosity is defined as the volume of water released from an aquifer per unit surface area per unit decline in water table depth below the surface, when the aquifer volume is fixed. Different terms are used for the concept of drainable porosity such as storage coefficient or specific yield (Freeze and Cherry, 1979; Ingram, 1983).

Total storativity is the sum of drainable porosity and the dilation coefficient, which is the volume of water expelled from saturated parts of an aquifer per unit surface area per unit decline in hydraulic head. The dilation coefficient is a fixed property of confined aquifers in mineral substrate (Freeze and Cherry, 1979). In contrast, the dilation coefficient has been defined differently in literature on peatland hydrology (cf. Kennedy and Price, 2005). Common practice for unconfined aquifers is to suppose that total storativity is equivalent to drainable porosity. Compression of (rigid) unconfined aquifers is usually presumed to be negligible (Freeze and Cherry, 1979). Therefore, neglecting aquifer compression assumes no differences between fluctuations of hydraulic head and water table below the surface. However, peat is compressible on account of its high porosity and weak architecture. Unexpected changes in water content in saturated peat layers due to changes in peat volume changes have been reported (Heikurainen et al., 1964; Schlotzhauer and Price, 1999). Peat volume changes, in addition to flotation of surficial peat layers, may result in elevation changes of the peat surface that are often neglected in water table monitoring. Thus assuming a stable surface in designing water table monitoring can introduce significant errors by underestimating storage changes by 40% to 70% (Kellner and Halldin, 2002; Price and Schlotzhauer, 1999). Also, water table monitoring relative to a fixed datum (eg. sea level) may overestimate water table fluctuations below the surface (Godwin and Bharucha, 1932; van der Schaaf, 1999) because some surface elevation changes are proportional to water table fluctuations (eg. Nuttle et al., 1990; Roulet, 1991).

Surface elevation changes were historically inferred from the disappearance of distant objects like churches (Eggelsmann *et al.*, 1993;

Weber, 1902), as the observer looks across the peatland at different times (during the day or year). However, these phenomena are mostly caused by refraction due to density differences in air layers (Weber, 1902). The first reliable measurement of surface elevation changes, amounting to 3.5 cm per season, dated back to 1900 (Weber, 1902). Weber (1902) used an iron rod set in firm layers below the peat body as a fixed elevation datum and the fluctuation of the surface level was measured against the iron rod. He called this phenomenon ‘rising and sinking of the surface’ (cf. Couwenberg and Joosten, 2002). Many other terms have been developed in the course of time such as ‘mire breathing’ (German: ‘Mooratmung’) (Overbeck, 1975), ‘topographic fluctuation’ (Almendinger *et al.*, 1986), ‘oscillation’ (of the mire surface) (Eggelsmann *et al.*, 1993) or ‘bog-breathing’ (van der Schaaf, 1999). In total 23 different terms for surface elevation changes in peatlands were found (Table F.1).

Surface elevation changes in peatlands include changes of the peat surface level above a fixed elevation datum (eg. sea level) due to reversible peatland surface oscillation, peat accumulation, irreversible subsidence, peat cutting, volume changes of underlying aquifers and geological crust movement. Seasonal peatland surface oscillation is the focus of this study. However, surface elevation changes is the overall term that encompasses all mechanisms and concerns reversible and irreversible changes in surface elevation.

As a rule of thumb, peatland surface oscillation coincides with seasonal moisture changes in peatlands (Baden and Eggelsmann, 1964; Buell and Buell, 1941; Ivanov, 1981; Kulczynski, 1949; Overbeck, 1975; Touber, 1973; Uhden, 1956; Weber, 1902). Overbeck (1975) recognised that peatland surface oscillation in peatlands occur regularly caused by water table up- and down movement. Nevertheless, little work has been done on the dynamics and spatial variability of reversible surface elevation changes in peatlands and what drives them.

1.3 Surface oscillation in peatlands in New Zealand

A stable peat surface has been assumed while designing hydrological monitoring in New Zealand’s peatlands. The use of benchmark rods (see Chapter 2.2) in water table monitoring is now a proposed standard

(Campbell and Jackson, 2004). Limited water table fluctuations have been observed in wetlands in the Waikato, New Zealand (Browne, 2005; Hodge, 2002; Thompson, 1997; Williamson, 1995). Campbell and Jackson (2004) speculated that an oscillating surface may reduce water table fluctuations in peatlands in the Waikato. Recent studies in Opuatia wetland suggested annual surface level oscillation of up to 23 cm revealing a high spatial variability (Browne, 2005).

Peatlands in the warm temperate climate of the North Island are suitable to study surface elevation changes over the period of years because monitoring is not hampered by snow, ice or gnawing beasts (Glaser et al., 2004; Kahrmann and Haberl, 2005).

1.4 Opuatia wetland complex

The majority of data discussed here were collected in Opuatia wetland (Figure 1.1), which is described in detail by Browne (2005). In brief, the Opuatia wetland complex is ca. 40 km north of Hamilton, North Island New Zealand (37°26'S, 175°04'E). The 950 ha peatland orientates along major faults perpendicular to the Kimihia fault (Mitchell and Edbrooke, 1988). This fault system has been active for millions of years providing a tectonic setting favourable for the development of extensive peatlands (today coal deposits of Te Kuiti Group) and may also determine the course of the lower Opuatia river, a minor lowland tributary of the Waikato River. The flooding regime of the Waikato river (mean annual flow 375 m^3 s^{-1} at Rangiriri, the closest river gauge (Environmental Waikato, 2006)) affects the hydrology of Opuatia wetland, when the Waikato river back floods the Opuatia river, which results in inundation of the wetland (Browne, 2005).

The 30-year average annual temperature of the closest climate station (40 km south of Opuatia wetland) was 13.7°C with average January and July temperatures of 18.9°C and 8.9 °C, respectively (NIWA, 2006). Mean (30 years) annual total precipitation was 1150 mm, typically with a late summer drought lasting 2-3 months.

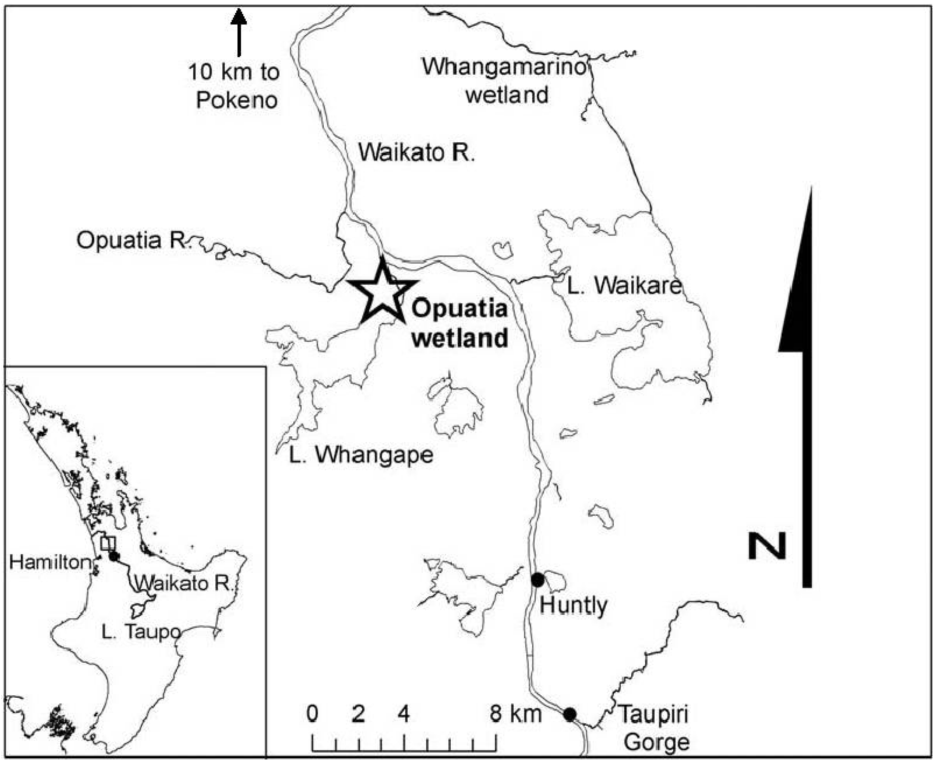

Figure 1.1: Location map of Opuatia wetland (adapted from Browne, 2005). The asterisk indicates position of the wetland.

Maximal peat thickness in Opuatia wetland was 12 m (field observation). The root peat in the upper 3.5 m was well-preserved usually underlain by highly decomposed silicate rich peats and flood deposits over impermeable clays commonly found in that region (Davoren *et al.*, 1978; Edbrooke, 2001). At 3.2-3.5 m depth the peat comprises a thin alluvial pumice layer, which was identified to be deposited subsequently to the Taupo eruption (1850 ± 10 ^{14}C years BP Lowe and de Lange, 2000), indicating average peat accumulation rates of more than 1.5 mm per year for the past 2000 years. The peat has not been subjected to drainage activities although the surrounding hill country was intensively used for dairy farming. However, changes in vegetation patterns indicate increase nutrient availability over the past decades (Browne, 2005; Clarkson, 2002). Likely sources of the additional nutrient load are farm run-off, nutrient contamination of the groundwater and river water discharging into the peatland and wind drift of fertiliser and soil.

The Opuatia wetland comprises various ecological wetland types as defined by Clarkson (2002) eg. swamp, fen and fen-young bog (Browne, 2005). The term ‘fen-young bog’ may be equivalent to ‘poor fen’ vegetation types (Sjors, 1950). Marginal sites with shallow and eutrophic peat and the flood plain of the Opuatia River were dominated by swamp species most prominently trees (*Salix ssp., Coprosma ssp.*) and shrubs (*Leptospermum scoparium*, *Coprosma ssp.*). Central parts of the peatland were covered by open vegetation, 0.8-1.5 m in height, comprising mainly fen-young bog species (*Empodisma minus, Gleichenia dicarpa, Baumea ssp., Schoenus ssp.*) but fen species were intermixed (*Phormium tenax, Dianella nigra, Baumea ssp.*). Fire is an important control of the vegetation dynamics in restiad peatlands in the Waikato (Clarkson, 1997; Clarkson, 2002; de Lange, 1989; Norton and de Lange, 2003). The last fire recorded in Opuatia wetland dates back to the early 1980s (P. de Lange pers. com.).

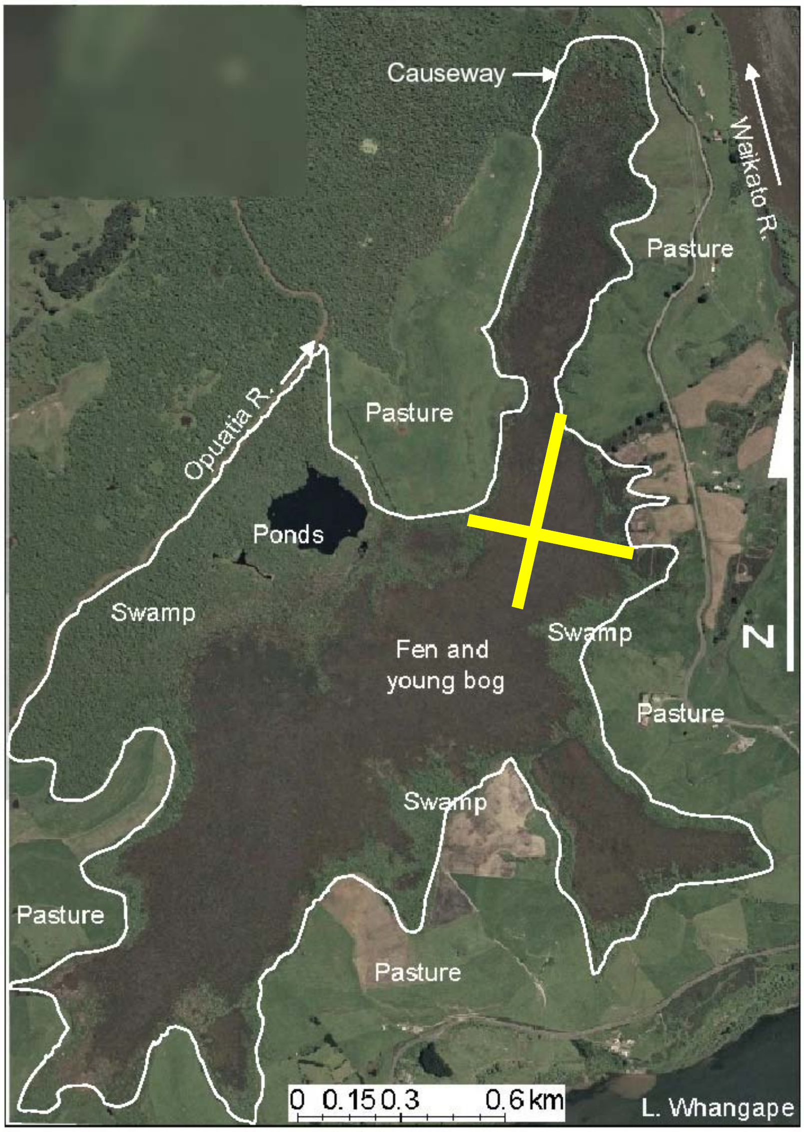

Figure 1.2: Aerial photograph of Opuatia wetland showing water bodies, wetland components and surrounding hills in pasture (adapted from Browne, 2005). The bright cross indicate the approximate position of the two transects discussed in Chapter 3. White line denotes the study area of Browne (2005).

1.5 Objectives

The overall goal of this research is to advance knowledge of surface oscillation in peatlands in general and particularly in a warm-temperate fen in the Waikato, New Zealand. The spatiotemporal variability of surface oscillation in the Opuatia wetland is compared with results derived from a literature review. The review explores methods to assess the extent of surface elevation changes in peatlands. Finally, implications of surface oscillation for regulating water table dynamics in peatlands are discussed with an emphasis on peatlands in the Waikato.

In detail objectives are to:

1. Prepare an overview of reported surface oscillation in peatlands worldwide with respect to range, spatiotemporal variability and driving forces of peatland surface oscillation.
2. Review methods to measure changes of the surface elevation and peat volume in peatlands to develop a reliable, simple and accurate method to assess peatland surface oscillation.
3. Test whether the relationship between surface level and water level is seasonally variable using a high resolution record over one year at one site and postulate links between this temporal variability and mechanisms causing peatland surface oscillation.
4. Clarify to what extent water table fluctuations, total peat thickness, dry bulk density and plant cover can explain the spatial and temporal variability of surface oscillation at 23 sites along two transects in Opuatia Wetland over one year.
5. Draw implications of surface oscillation for peatland hydrology.

1.6 Thesis outline and composition

The core of this research is presented in Chapters two and three, which have been written in the form of papers. Chapter 3 has already been submitted to 'Hydrological Processes.' This results in some duplication, particularly in introduction sections.

The literature review (Chapter 2) emphasises methods to measure the spatiotemporal variability of surface oscillation between and within studies. Patterns of surface oscillation are analysed according to peatland types such as disturbed peatlands, fens, bogs and floating peatlands. Possible mechanisms for surface oscillation in peatlands are reviewed providing a basis for interpreting the field study.

Chapter three describes a new method (using two water level transducers) to assess surface elevation changes at high time resolution. The spatiotemporal variability of surface elevation changes recorded manually at 23 sites over a one-year period in Opuatia Wetland is presented. Emphasis is put on where and when a linear relationship between the absolute elevation of water table and peat surface exists. A new format to present water table related data in peatlands is developed.

Chapter four extends the discussion of previous chapters and postulates that the restiad plant, *Empodisma minus,* partly controls fluctuations of the water table below the surface via surface oscillation by increasing the gas content of its roots. The importance of peatland surface oscillation is highlighted by discussing the regulative effects an oscillating surface has on peatland hydrology.

The appendices contain additional data including a hysteresis model that supports results and discussion presented in Chapter three. However, the brief style of Chapter three required that this valuable material is moved to the appendix. The precision of the method developed to measure surface elevation changes in peatlands is analysed followed by the presentation of two more continuous datasets of surface level and water level fluctuations. One key element of the appendix is a sequence of four simulations concerning hysteresis of surface oscillation derived from a simplistic model of the delay in surface oscillation. A substantial part of the seasonal variability of surface oscillation can be explained with the help of these simulations. The appendix also contains detailed tables of literature review data and field study data.

Chapter 2

Reversible change in surface elevation in peatlands: why is it important for water table controlled processes?

Abstract

Hydrology, particularly the water table position below the surface (relative water level, RWL), is an important control on biogeochemical and ecological processes in peatlands. The absolute surface level (ASL) in a peatland oscillates seasonally affecting RWL. A review of 37 studies on seasonal, reversible ASL changes (=peatland surface oscillation, PSO) indicate a wide range (1-19 cm, 95% confidence interval) that is to the same order as (or one order smaller than) water storage changes and RWL fluctuations. PSO is driven by a set of mechanisms (flotation, compression/shrinkage, gas volume changes and freezing). ASL changes and absolute water level fluctuations often co-vary eg. due to flotation or compression/ shrinkage, resulting in smaller RWL fluctuations, increased water storage and reduced probability of surface run-off. The potential to reduce RWL fluctuations trended (mean): floating peatlands (63%)> bogs (21%) and fens (18%) >disturbed peatlands (10%) in respect to peatland types. Moreover, PSO varies substantially across a single peatland. We conclude that seasonal ASL changes should be considered in water table monitoring using automatic water level and surface level transducers that are attached to a metal rod benchmark fixed in firm substratum. Further research should focus on the spatiotemporal variability of PSO and its control on hydraulic parameters such as total storativity and hydraulic conductivity.

2.1 Introduction

The surface level in a peatland oscillates seasonally (Eggelsmann et al., 1993; Ingram, 1983). Besides total storage changes and total storativity it is the surface level that determines the position of the water table below the surface, which is an important control on biogeochemical and ecological processes in peatlands (cf. Blodau, 2002). Weber (1902) reported surface levels in a Russian peatland 3.5 cm higher during winter than during summer and called this phenomenon ‘surface movement’. Observations of water table and absolute surface level (ASL) in different peatlands indicate that the surface level oscillates following water level fluctuations (FechnerLevy and Hemond, 1996; Green and Pearson, 1968; Nuttle et al., 1990; Price, 2003; Roulet, 1991) as shown in Figure 2.1. Generally, the water table position in peatlands can be defined in two ways (Figure 2.1): the water table position above an absolute elevation datum eg. sea level (absolute water level, AWL) and the water table with respect to the oscillating surface (relative water level, RWL).

Water balance studies suggest that monitoring RWL instead of AWL can introduce significant errors by underestimating storage changes by 40% to 70% (Kellner and Halldin, 2002; Price and Schlotzhauer, 1999). Also, water table dynamics monitored as AWL may substantially overestimate water table fluctuations with respect to the surface (Godwin and Bharucha, 1932; van der Schaaf, 1999).

Water content of the saturated and unsaturated zones is essentially dependent on RWL (Heikurainen et al., 1964; Okruszko, 1995; Schlotzhauer and Price, 1999) affecting redox processes in peat (Barber et al., 2004; de Mars and Wassen, 1999) and plant community distribution (Clymo and Hayward, 1982; Kotowski et al., 1998; Wierda et al., 1997). As a rule of thumb, lowering of the water table results in increasing CO_2 and decreasing CH_4 emission rates and, by contrast, water tables close to or above the surface promote relatively low CO_2 and high CH_4 emission rates (Blodau, 2002; Bubier et al., 2003; Freeman et al., 1992; Moore and Knowles, 1990; Moore et al., 1998; Scott et al., 1999). Limited water table fluctuations and water tables close to but below the surface are necessary for fast peat accumulating systems (Bauer 2004; Belyea and Clymo, 2001;

Hilbert et al., 2000), effective restoration of peat forming vegetation (Price et al., 2003; Smolders et al., 2002) and highly productive peat moss farming (Gaudig et al. in press). Water tables above the peat surface may lead to high rates of water loss via increased surface run-off (Hemond, 1980; van der Schaaf, 1999), and erosion (Warburton et al., 2004).

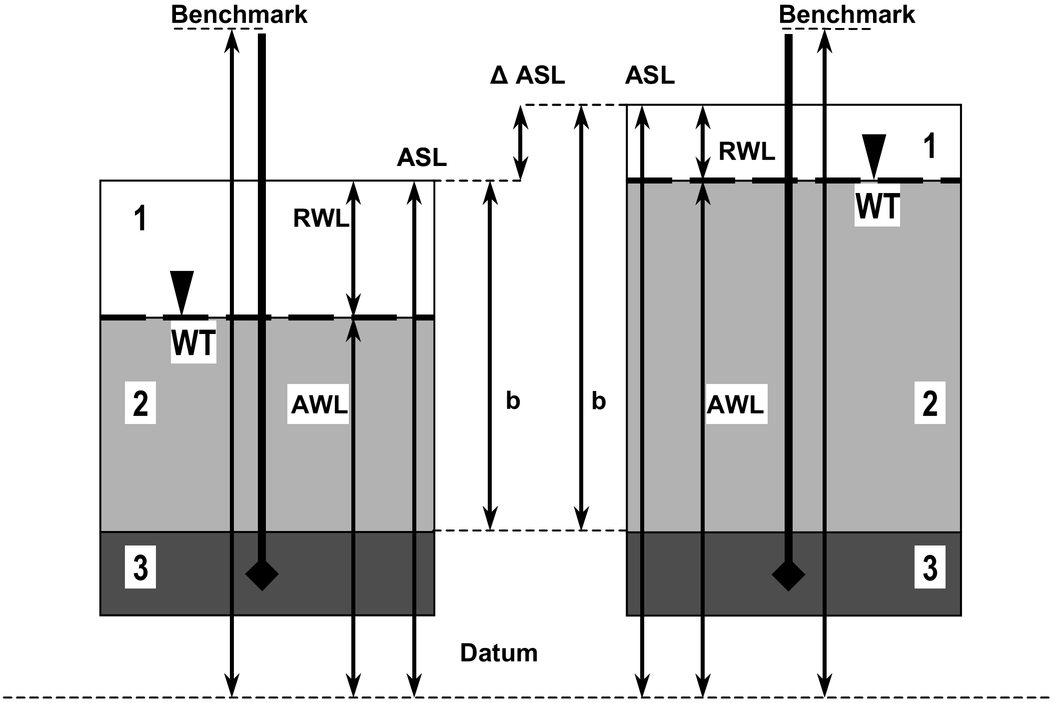

Figure 2.1: Definition diagram showing how differences in water table (WT) positions depend on changes of the absolute surface elevation (ASL): Stable datum (eg. steel rod) anchored in firm substratum (3) remains constant. In this illustration peat thickness increases by the surface elevation change (ΔASL) from time 1 on left to time 2 on right. ΔASL coincides with a rise of the absolute water level (AWL). The saturated zone thickness (2) increases at the expense of the relative water level (RWL - water table position in respect to the moving surface). The WT would reach the surface at time 2 (right) without ΔASL. In contrast, the increasing peat volume prevents a sharp decrease of the unsaturated zone thickness (1). Thus the difference in RWL (time 1 on left to time 2 on right) is reduced. The total fluctuation in ASL is called peatland surface oscillation (PSO) if ASL changes are more-or-less reversible.

The absolute surface level can change (ΔASL in Figure 2.1) as a result of peat volume changes including the development of water cushions (Price, 2003; Stegmann et al., 2001), volume changes of underlying aquifers (Freeze and Cherry, 1979; Whelan et al., 2005) and long-term earth crust movement or sea level rise. In this paper we focus on seasonal and reversible ASL changes in peatlands, or peatland surface oscillation (PSO). Beside the concept of reversible ASL changes, PSO as a number equals the total (reversible) fluctuation in ASL. PSO occurs when peat volume changes reversibly due to altered volume of pores (compression/ shrinkage). That includes total volume changes of water filled cavities along the peat profile (cf. floating peatlands). However, long-term irreversible subsidence of peatland soils also occurs (Eggelsmann, 1978; Holzer, 1984; Schipper and McLeod, 2002; Wosten et al., 1997). Irreversible peat volume changes can be induced by changes in carbon balances (sequestration/ release) (Clymo, 1984; Schothorst, 1977) or irreversible compaction of peat (Hobbs, 1986; Kennedy and Price, 2005). Schothorst (1977) suggested that irreversible subsidence is superimposed on PSO. In that study annual ASL oscillation significantly exceeded subsidence rates.

Data about the magnitude of PSO are limited. In Table 2.1 we summarise 37 studies discussing methods used to measure PSO, extent of PSO and suggested mechanisms causing PSO. Relationships between PSO, peat thickness, and AWL fluctuation as well as peatland type are examined. Finally, we discuss implications of PSO for peatland hydrology.

2.2 Methods to assess peatland surface oscillation

To detect changes of the surface level (ASL) it is necessary to use benchmarks that provide an arbitrary elevation datum, which remains unaffected by ASL changes. Commonly used and reliable benchmarks are steel rods set into firm substratum being separated from the surrounding peat with a bigger diameter tube (eg. van der Schaaf, 1999; Van Seters and Price, 2001; Weber, 1902). Engineering constructions (eg. power pylons) fixed to the substratum (Almendinger et al., 1986; Hutchinson, 1980) or satellites, by deploying a Global Positioning System (GPS) network have also served as benchmarks (Glaser et al., 2004).

After establishing a benchmark and a mark/tag on the peat surface, elevation changes of the surface can be monitored by measuring the vertical distance between benchmark and surface mark (Figure 2.1). In order to assess elevation change in individual peat layers light-weight rods, protruding from the surface, or discs have been anchored in the peat matrix at different depths (Eggelsmann, 1981; Gilman, 1994; Kennedy and Price, 2005; Price, 2003; Schothorst, 1977). Moreover, Price and Schlotzhauer (1999) deployed an indirect method to assess the amount of elevation changes of peat layers below the water table by measuring moisture content changes in saturated peat.

Monitoring of PSO at a high temporal resolution has been achieved by automatic level recorders, mounted on a benchmark and connected to the peat through a pulley system (FechnerLevy and Hemond, 1996; Green and Pearson, 1968; Price, 1994; Roulet et al., 1991; Swarzenski et al., 1991; Tsuboya et al., 2001). A GPS network may also facilitate a continuous record (Glaser et al., 2004).

Pitfalls

Peatland surface oscillation measurements from the literature show a magnitude of centimetres per year (Table 1) and, consequently, assessment of ASL changes requires a high accuracy and precision. Measurements become unreliable if the benchmark elevation varies significantly (in the order of ASL changes): Gilman (1994) found deviation of the benchmark height of up to 15 cm after re-surveying using a dumpy level. He concluded that the silt substrate in this case provided less friction than layers of clay and dense peat in the overlying peat shifting the benchmark, which was not separated from surrounding peat. Shallow tubes may be unreliable benchmarks (eg. 1 m deep dipwells used by Price and Schlotzhauer, 1999)) because tubes are not anchored in steady substrate and unfixed tubes may be pushed up when peat expands (field observation). In contrast, dipwells penetrating into mineral substrata (Kellner and Halldin, 2002) and piezometers placed in deep peat layers (van der Schaaf, 1999) have revealed small elevation fluctuations (+/- 1 cm). Deploying a GPS system requires careful processing of the elevation data due to the system's inherent noise and a wobbling earth (Lambert et al., 2006).

Instead of marking the surface, trees rooting in peat have been tagged and surveyed (Almendinger et al., 1986; Buell and Buell, 1941; Glaser et al., 2004). However, trees can sink into the peat and are moved by wind reducing their suitability to indicate the peat surface elevation. Fluctuating gas contents in peat hampers assessing elevation changes of peat layers below the zone of water table fluctuations by measuring soil moisture changes in the saturated peat eg. (Price and Schlotzhauer, 1999). Moreover, surplus burden (body weight) (Nuttle et al., 1990) and disturbing plant cover (Hogg and Wein, 1988a) can result in significant measurement errors.

2.3 Review of studies concerning surface oscillation in peatlands

2.3.1 Methods and conventions used in this review

We estimate the total range of PSO and variation of PSO according to peatland type by summarising 37 studies comprising in total 79 measurements of reversible surface elevation changes in peatlands (Table 2.1). The summary includes peatland type, peat thickness, total AWL fluctuations, total RWL fluctuations, total reversible change in surface elevation (PSO) and duration/season of observation. Conversions of the original data were necessary, particularly water levels. In case of no distinction between AWL and RWL, water table data related to the surface are assumed to be RWL. Suitable for our purpose, AWL fluctuations can be calculated by adding total change in surface level elevation to total RWL fluctuations (Figure 2.1). Conversely, total RWL fluctuations derive from measured AWL range less the total surface elevation fluctuations. This is a conservative estimate if the relationship between AWL and ASL varies in time because then overall RWL fluctuations may exceed RWL fluctuations calculated from ranges AWL and ASL (eg. Roulet et al., 1991). Additionally, irreversible subsidence should be excluded in order to calculate merely reversible ASL changes. Only long-term studies allow for excluding subsidence (eg. Schothorst, 1977). In Table 2.1 studies are printed in bold where we suspected subsidence to be incorporated in ASL changes. However, the introduced error is small because the proportion of subsidence due to irreversible volume loss may be one magnitude smaller than reversible ASL changes over one growing season as argued by Kennedy and Price (2005). Therefore, the total fluctuation in ASL is assumed to equal PSO. For several studies data are drawn from published figures or raw data provided by the author(s).

We distinguish here four peatland types: Disturbed peatlands (cutover and drained peatlands), fens, bogs and floating peatlands. This classification is inconsistent according to Joosten & Clarke (2002) but it highlights the unique nature of floating systems. This classification also respects the disturbance that peatlands have been subjected to due to large changes in water regime, soil physics and plant communities. To condense information the range of observed variables (eg. water table fluctuations, peat thickness) is provided for studies that extend over several years or comprise several sites in the same peatland type. Yet, results are listed separately according to every site if studies were conducted in the same peatland complex comprising different peatland types (Table 2.1). Figures 2.2 and 2.3 include each individual measurement (year/site) as long as the required variables are reported (Table G.1).

Reversible ASL changes were recorded over a wide range of total AWL fluctuations amongst the studies (Figure 2.2a). This may bias the analysis of PSO if AWL fluctuations control PSO. Therefore, a normalisation of PSO data are required. Normalised PSO data is presented as the oscillation coefficient (OSC, dimensionless), which is PSO divided by the total AWL fluctuations (cf. total ΔASL divided by total ΔAWL). If the ASL-AWL relationship is more-or-less linear, OSC equals the slope of the ASL-AWL curve.

Table 2.1: Summary of reviewed studies ordered according tt9 the peatland type. Column 3 (Period and frequency) comprises of study period, the season in which study commenced and the measurement frequency. Abbreviations are as follows:

1. Duration in years;
2. Season: sp=spring, s=summer, a=autumn, w=winter;
3. Frequency: con=continuous, d=daily, w=weekly, f=fortnightly, m=monthly, qua=3-monthly, hy=6-monthly, y=yearly.

The minimum and maximum range of values of each variable recorded in different years and/or at different sites in the same peatland type is presented for some studies. However, Figures 2.2 and Figure 2.3 comprise the total fluctuations of variables for every year and site, respectively.

Peat-land type	Reference	Period, frequency	Peat thick-ness [m]	AWL [cm]	RWL [cm]	PSO [cm]	Term
disturbed peatlands	**(Price and Schlotzhauer, 1999)**	0.4, s, d	1.7	55-80	-	7.0-9	peat volume changes
	(Price, 2003)	0.5, s, f	1.7-2.9	-	40-75	4.0-7.5	peat volume changes
	(Kennedy and Price, 2005)	0.3, s, f	1.7-2.9	-	26-46	2.5-5.5	peat volume changes
	(Kennedy and Price, 2005)	0.1, s, w	1.7	-	18-38	0.7-5.3	peat volume changes
	(Van Seters and Price, 2001)	0.25, s, f	4-4.6	-	20.0-33.4	1.0-1.6	surface elevation changes
	(Whittington and Price, 2006)	0.25, s, w	0.8	11.0-16.0	-	1.0	peat volume changes
	(Gilman, 1994)	4.75, sp, f	3.7-5.4	29-70	-	3.4-9.4	ground movement
	(Gilman, 1994)	2, sp, f	4.5-5	90	-	7.0-13.0	ground movement
	(Schothorst, 1977)	6, sp,qua	7	20-55	-	2.0-8.0	surface elevation fluctuation
	(ter Hoeve, 1969)	1.1, w, m	3.5-3.9	15-28	-	2.0-3.3	Mooratmung
	(Barber et al., 2004)	6,-,-	6	100	-	6	soil elevation changes
	(Eggelsmann, 1981)	-	-	-	18-72	0.7-4.2	oscillation
	(Baden & Eggelsmann, 1964)	-	-	-	-	1.5-3	Mooratmung
	(Eggelsmann, 1964)	-	-	-	-	2.3-6	Mooratmung

Table 2.1 continued.

Peat-land type	Reference	Period, Frequency	Peat thick-ness [m]	AWL [cm]	RWL [cm]	PSO [cm]	Term
fens	(Price, 1994)	0.25, s, con	0.6	40	-	0.8	surface adjustment
	(Almendinger *et al.*, 1986)	1, s, hy	2.2-2.6	-	-	1.5-6	topographic fluctuations
	(Glaser *et al.*, 2004)	0.33, s, con	3	-	2.5	6-	surface deformation
	(Tanneberger and Hahne, 2003)	0.33, s, w	3.5-5.2	8.0-12.0	7.5-13.50	0.5-4.5	fluctuation in levels
	(Schipper and Loss, 2003)	0.33, s, w	4.2	-	7.75	2.5	mire oscillation
	(Swarzenski et al., 1991)	0.17,a, w	0.5	45	42	3	surface movement
	(Whittington and Price, 2006)	0.25, s, w	1.2	7.7	-	1.5	peat volume changes
	(Touber, 1973)	0.25,s,m	0.6	10	-	1	Kragge movement
	(Touber, 1973)	0.25,s,m	0.6	8.0-10.0	-	0.5-1	Kragge movement
	(Nuttle et al., 1990)	0.25,s,d	1.0-4.5	12.0-27.0	-	0.4-2.3	surface displacement
	(Kellner et al., 2005)	1.33, s, w	1.2	-	14-22	9.0-10.0	peat volume changes
	(Holm et al. 2000)	1,sp,qua	-	60-120	-	3-30	vertical (mat) movement
bogs	(Tsuboya et al., 2001)	0.25,s,con	6	16-23	-	5.0-7	surface movement
	(van der Schaaf, 1999)	1.1, sp, f	2.9-12.5	-	15.0-40	4.9-6.7	bog breathing, seasonal
	(van der Schaaf, 1999)	2.2, sp, f	4.5-8	-	12.0-36.0	3.2-10.9	oscillation of the surface level
	(van der Schaaf, 1999)	2.2, sp, f	-	-	-	2.6-5.9	see above
	(Baumann, 2006)	0.25, s, w	4.5-7	-	14.5-30.0	6.0-10.0	mire oscillation
	(Glaser *et al.*, 2004)	0.33, s, con	4.3	-	11	4	surface deformation
	(Almendinger *et al.*, 1986)	1, s, hy	4	-	-	11	topographic fluctuations
	(Kellner and Halldin, 2002)	1.5, s, con	3.5	30	-	4	mire breathing
	(Fox, 1984)	2.25, sp, con	7	13	-	6.4	mire breathing
	(Uhden, 1967)	-	-	-	-	4.0-5.0	Mooratmung
	(Uhden, 1956)	-	-	-	-	7.0-11.0	Atmen der Hochmoore

Table 2.1 continued.

Peat-land type	Reference	Period, Frequency	Peat thick-ness [m]	AWL [cm]	RWL [cm]	PSO [cm]	Term
floating peatlands	(Price, 1994)	0.25, s, con	2.6-5	34-40	-	10.0-12.0	surface adjustment
	(Roulet, 1991)	0.17, s, w	1.5	5-10.6	0-4	3.1-10.6	fluctuations of the surface level
	(Fechner-Levy and Hemond, 1996)	0.5, s, con	2	21	3	18	absolute floating mat level changes
	(Gates, 1940)	17, s, y	3.9	-	-	67.1	level fluctuation
	(Buell and Buell, 1941)	5, a, hy	10	70[1]	-	11.9-45.1	surface level fluctuation
	(Koerselman, 1989)	1,sp, w	0.6	20	-	3.5	root mat oscillation
	(Swarzenski et al., 1991)	1, s, con	1.3-1.6	70	18-50	35-55.0	surface movement
	(Green and Pearson, 1968)	2, w, w	4	17	10	12	peat raft movement
	(Touber, 1973)	0.25,s,m	0.6	3.0-23.0	-	0.5-12	Kragge movement
	(Whittington and Price, 2006)	0.25, s, w	1.2	7.5	-	6.5	peat volume changes
	(Roulet et al., 1991)	0.25,s,con	1.5	9.5	9	4.4	surface fluctuation
	(Baird et al., 2004)	-	-	-	-	5.0-10.0	vertical (mat) movement
	(Hogg and Wein, 1988)	-	0.5	-	3	-	mat buoyancy

2.3.2 Range and variability of peatland surface oscillation

The range of reviewed peatland surface oscillation is 0.4–55 cm. Excluding floating peatlands, PSO amounts to 1-10 cm (95% confidence interval, mean 4 cm) without any trend amongst peatland types (Figure 2.2b), whereas disturbed peatlands have typically higher AWL fluctuations (Figure 2.2a). When comparing on the basis of OSC peatland types exhibit trends (Figure 2.2c). Floating peatlands show high values of PSO (2.5–55 cm, mean 11 cm) and also high OSC (0.18-1.00). These high OSC values suggest that the surface oscillates by 0.18 to 1 cm per 1 cm fluctuation in AWL. Conversely, disturbed peatlands show a much lower OSC range (0.04-0.15; Figure 2.3c). OSC of fens and bogs varies, but more than half of the reported measurements exceed 0.15, which is the upper limit for disturbed peatlands. Thus, peatlands with lesser human impact (ie. 'fens' and 'bogs') have a higher ability to modulate water table fluctuation

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[1] 70 cm was the total fluctuation of the lake level.

through PSO than peatlands highly impacted by hydrological changes. Moreover, floating peatlands can reduce almost all RWL fluctuations, particularly in cases of ideal flotation (OSC≈1 cm/cm) (eg. Roulet, 1991).

Few data are available on seasonal fluctuations of PSO, ie. the surface stops oscillating during some part of the year or during high or low AWLs. Generally, PSO is a function of AWL fluctuations, so that the surface elevation fluctuates in a peatland according to seasonal changes in AWL (FechnerLevy and Hemond, 1996; Kennedy and Price, 2005; Nuttle et al., 1990; Tsuboya et al., 2001). However, PSO can become inhibited in floating peatlands during high AWLs (Koerselman, 1989; Swarzenski *et al.*, 1991) or low AWLs (Green and Pearson, 1968; Schwintzer, 1978; Swarzenski et al., 1991) promoting a prompt increase in RWL fluctuations. Many floating peatlands in this review show a OSC well below 1 (mean 0.63) suggesting that the peatland type can alter during the course of a study, ie. grounding of a floating peat layer. Flotation ceases then for some time resulting in much lower OSC, as AWL changes cause very little surface elevation changes (FechnerLevy and Hemond, 1996; Roulet et al., 1992; van Wirdum, 1991). Hence, floating peatlands may be subjected to seasonal and long-term changes in OSC. Seasonal differences in ASL changes for an equivalent fluctuation in AWL in non-floating system have been reported by Kennedy and Price (2005) who speculated that winter frosts increased the compressibility of peat, which declined during the growing season decreasing the potential for PSO.

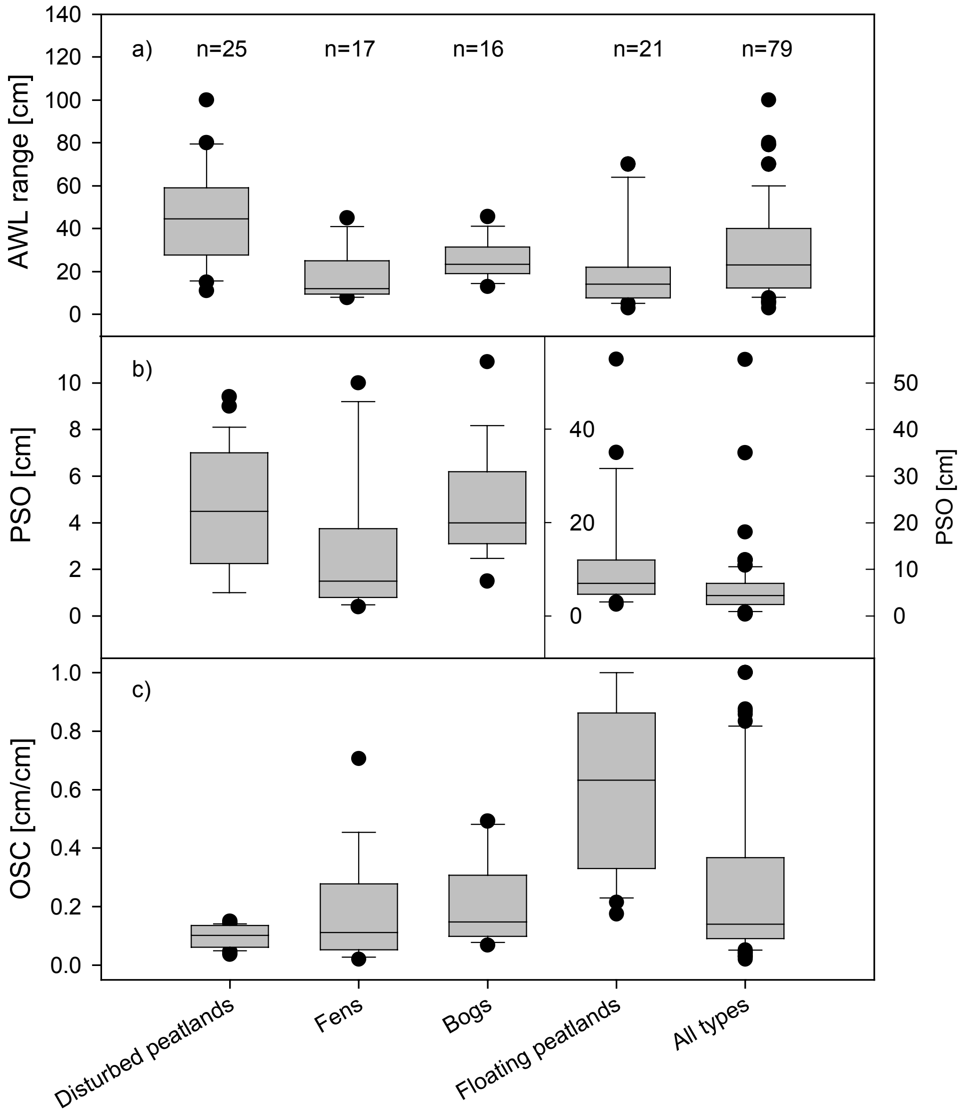


Figure 2.2: AWL fluctuations, PSO and OSC in boxplots according to peatland type. Boxes represent the variability of sites and years of a) total absolute water level (AWL) fluctuations, b) Range of peatland surface oscillation (PSO) and c) oscillation coefficient (OSC), which is PSO divided by total AWL fluctuation for every record. PSO of floating peatlands and all types is plotted in five times larger scale. The central crossbar represents the median; the boxes the 75th and 25th percentile; the upper and lower bars, the 90th percentile; the dots, extreme values of the displayed data set.

PSO is spatially variable across single peatlands (Baumann, 2006; Buell and Buell, 1941; Gilman, 1994; Price, 1994; Price and Schlotzhauer, 1999; Roulet, 1991; Tanneberger and Hahne, 2003; ter Hoeve, 1969; Touber, 1973; Whittington and Price, 2006). Studies in temperate bogs found higher PSO in the centre than at the margins where peat is generally shallow and dense (Baumann, 2006; Fox, 1984; van der Schaaf, 1999).

The amount of surface elevation change due to volume changes of peat is theoretically positively correlated to peat thickness (Ivanov, 1981; Terzaghi, 1943). Almendinger and co-workers (1986) claimed that peat thickness largely controls PSO variability. Amongst the reviewed studies peat thickness explains only a small part of the variation in OSC (r^2=0.11 or r^2=0.06 if peat thickness is related to PSO, n=58; Figure 2.3). The relationship within types is even weaker (Figure 2.3). Measurements of elevation changes in individual peat layers suggest that volume changes of peat are confined to the upper 1 to 1.5 m of peat (Gilman, 1994; Price, 2003). Some 80% of the peatlands discussed consist of >1.5 m of peat suggesting that little of the variation in PSO is controlled by the total peat thickness alone. Conversely, Schothorst (1977) noted little difference between elevation changes of top layers and peat layers at 1.40 m depth, which highlights the heterogeneity of peatlands.

Disturbed peatlands show low OSC and are often associated with shallow and consolidated peat, potentially limiting PSO. Reversible and irreversible changes in ASL are spatially sensitive to drainage: ASL changes decrease as distance to drainage devices decreases (Gilman, 1994; Price and Schlotzhauer, 1999; Whittington and Price, 2006). Close to ditches PSO is generally very small (0-1 cm) and bulk density of peat is highest. Holm et alii (2000) found that PSO was small when bulk density of peat increased in oligohaline fens in North America. Hence the architecture of the upper peat (1-2 m) and bulk density may explain a substantial part of the spatial variability of PSO.

Whittington & Price (2006) observed differences of several cm in PSO on the scale of hummocks, lawns and hollows with presumably no differences in peat thickness: the lawn site showed larger PSO (6.5 cm) than the hummock/pool site (1 cm) being only several metres apart and subjected to the same AWL fluctuations (7.5 cm). The authors concluded that the lawn site can float in contrast to hummock and pool sites. Hence, the wide range of OSC reported for fens and bogs may be the result of spatial variability and seasonal flotation of upper peat layers.

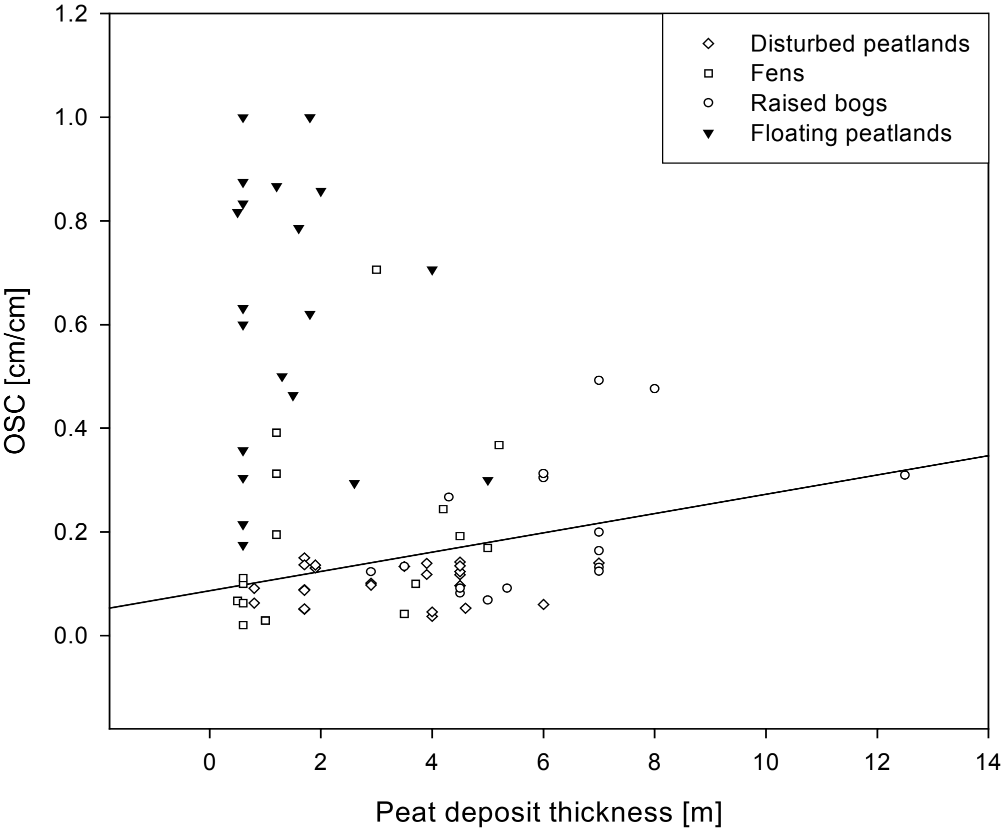


Figure 2.3: Relationship between peat thickness and oscillation coefficient, which is the total PSO range divided by total AWL fluctuation for every record. Solid line represents a linear regression model (r^2=0.11, n=58), when floating peatlands are omitted.

2.4 Possible mechanisms causing PSO

2.4.1 ASL changes and forces on the peat matrix

Early investigators assumed ‘peat swelling’ after rewetting as the main cause for PSO (Weber, 1902). Many studies agree that surface elevation changes coincide with AWL changes (Figure 2.4, Baumann, 2006; FechnerLevy and Hemond, 1996; Green and Pearson, 1968; Nuttle et al., 1990; Price and Schlotzhauer, 1999; Roulet, 1991; Tsuboya et al., 2001). In contrast, Price (2003) found the surface risen by 1-2 cm while the water table (AWL) receded by some 10 cm in a North American bog. Moreover, Glaser and co-workers (2004) hypothesised gas ebullition to cause short term surface movements independently from AWL changes.

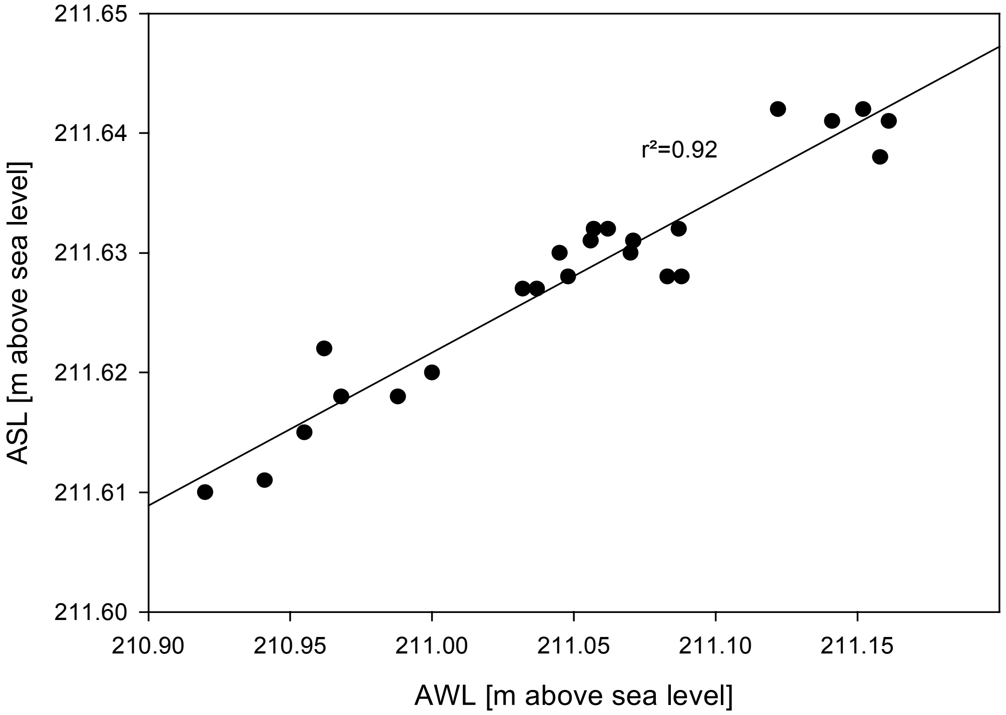


Figure 2.4: Linear relationship between absolute water level (AWL) and absolute surface level (ASL) for a temperate raised bog in South Argentina. With permission from Baumann (2006).

All together five mechanisms have been hypothesised to cause PSO, eg. flotation, compression, shrinkage, freezing and gas accumulation, which are driven by gravity and material stress. All mechanisms cause peat volume changes of the peat body, which includes water filled cavities (water cushions). In essence, the surface of a peatland remains stable as long as upward and downward forces imparted on the peat matrix are in equilibrium (Ivanov, 1981; Kennedy and Price, 2004; Stegmann et al., 2001). Prevailing downward forces, mainly weight of the peat and burden of the vegetation, result in peat compression (shrinkage) limited by the compressibility (shrinkage characteristic) of the peat matrix. In the case of prevailing upward forces, most prominently buoyancy and pore water pressure, peat expands limited by the peat's inherent tensile stress. If upward forces exceed the tensile stress, peat layers become detached, and thus floating, as discussed later. For a complete overview of forces imposed on peat layers see Ivanov (1981).

Compression and shrinkage are partly irreversible (Hobbs, 1986; Price et al., 2005) and hence long-term subsidence occurs if more volume is lost by irreversible compression/shrinkage/oxidation than gained by peat formation (Camporese et al., 2006; Schipper and McLeod, 2002; Schothorst, 1977). In pristine peatlands irreversible volume losses are counteracted by peat forming vegetation refurnishing the system with highly porous material (Clymo, 1983).

2.4.2 Mechanisms

FLOTATION

Flotation of peat 'rafts' is the simplest form of PSO and the concept of a separated top peat layer is important for the distinction of flotation from other mechanisms (Stegmann et al., 2001). The separation of the topmost peat may originate from colonisation of a lake by peat forming vegetation (Kratz and DeWitt, 1986) or a break free from the underlying substratum (Ivanov, 1981; Tallis, 1983). So, the 'whole' top layer is subject to elevation changes. According to Kulzczynski (1949) water saturated peat is commonly less dense than water (buoyant) due to gas entrapped in peat (Kellner et al., 2005) and in underground plant tissues (Hogg and Wein, 1988a; Mainiero and Kazda, 2005; Sculthorpe, 1967). Hence, buoyant peat can equally move up and down with AWL fluctuations (ideal flotation) reducing all RWL fluctuations. However, RWL fluctuations of several centimetres have been observed in floating peatlands indicating inhibited flotation (FechnerLevy and Hemond, 1996; Green and Pearson, 1968; Hogg and Wein, 1988b; Price, 1994; Roulet, 1991; Roulet et al., 1992; Strack et al., 2005; Swarzenski et al., 1991; van Wirdum, 1991). Causes for inhibited flotation are: changing buoyancy (force), 'grounding' and horizontal strain if the peat is attached to the mineral margins or non-floating peat.

COMPRESSION AND SHRINKAGE

Peat is very compressible on account of its fragile architecture and high porosity (Hobbs, 1986; MacFarlane, 1965). Volume changes of peat are caused by collapsing pores, which increases or by expanding pores, which decreases bulk density. Peat volume changes below the water table are traditionally called compression. Compression refers also to swelling of the peat matrix (reversed compression). Shrinkage refers to peat volume changes above the water table (unsaturated zone). A lower water table decreases pore water pressure in the unsaturated zones amplifying the effective stress (as defined by Terzaghi, 1943)) on the peat matrix, consequently the peat shrinks. Further, when the water table is lowered, the peat matrix below the water table (after lowering) collapses because of the increased weight due to buoyancy loss of the peat that becomes unsaturated. Price and co-workers (2005) found that peat characteristics such as bulk density, degree of decomposition and fibre content were unreliable indicators for compressibility. Schothorst (1977) reported that 35% of the total ASL changes derived from compression for a Dutch fen comparable with results from a Canadian bog suggesting 50% contribution by compression to 2.5 cm total PSO (Kennedy and Price, 2005). Both studies attributed the remaining elevation changes to shrinkage and to a small extent to annual peat decomposition. However, these figures may be not representative because both peatland were deeply drained.

Compression becomes less noticeable in dense peats (eg. high ash content)(Hobbs, 1986) and in peats compacted and stressed by drainage and peat extraction machinery (Kennedy and Price, 2004). In addition to peat porosity (quality) the total amount of compression should be also positively related to peat thickness (quantity). Shrinkage is more important in peatlands with large RWL fluctuations, where a deep unsaturated zone is periodically exposed.

GAS VOLUME CHANGES

An increased gas volume in peat can raise the surface in peatlands independent from AWL fluctuations. In short, nitrogen and methane, the prevailing gases in saturated peat (Hogg and Wein, 1988b), derive from peat decomposition and atmospheric input (see review on gas bubble formation by Strack et al., 2005). Gas content in peat, commonly 5-15% by volume (Kellner et al., 2005), is closely related to ambient temperature as higher temperatures increase gas formation, gas volume and decrease gas solubility (Hogg and Wein, 1988b). Buoyancy is strongly controlled by gas content eg. a methane content of some 5% makes peat buoyant (Strack *et* *al.*, 2005). However, changes in buoyancy only shift the equilibrium of upward and downward forces imposed on the peat matrix resulting in compression or flotation.

Gas bubbles occupy a certain volume (voids) in the peat matrix that can suddenly collapse, when gas is rapidly released (ebullition). These peat volume changes may cause a deformation of the peat surface and have been detected by GPS with a magnitude of more than 20 cm in 4 hours in a North American peatland (Glaser et al., 2004). The surface movements coincided with depressuring cycles in a 3 m deep overpressured stratum suggesting gas ebullition. However, these high ebullition rates are extreme in comparison to other studies (FechnerLevy and Hemond, 1996; Strack et al., 2005). In conclusion, ASL changes due to ebullition of several centimetres need to be confirmed by further research using methods that are more accurate than GPS antennae mounted on trees.

FREEZING

In climates with frequent frosts, ice formation will inevitably cause ASL changes since water expands on freezing. Hence, ice can potentially reduce the consolidation of compressed peat, whereas the effect of stabilising ice on the peat matrix ceases after thawing, exposing the peat to consolidation (Kennedy and Price, 2005). In this way, Roulet (1991) related PSO partly to the depth of thaw in a subartic fen. Furthermore, Weber (1902) described winter surface levels in frozen peat to be 10 cm higher than summer surface levels for a temperate bog. Besides, the elevation in floating palsas respond to changes in ice thickness/volume emphasising the importance of increased substrate buoyancy due to ice formation (Outcalt and Nelson, 1984).

2.5 Implications of PSO for peatland hydrology

Surface oscillation has many regulative effects on water fluxes, eg. increasing water storage and preventing surface run-off. Flotation, compression and shrinkage are strongly related to AWL fluctuations and store additional water below the peat surface (Kennedy and Price, 2005). Reducing RWL fluctuations may be the most important effect of PSO on peatland hydrology. PSO mechanisms such as compression/shrinkage and flotation cause a reduction in RWL fluctuations: lowering of the AWL exposes a larger proportion of the peat to shrinkage and reduces buoyancy leading to an increase in downward forces (eg. weight of unsaturated peat) that compresses the peat below the water table. As a result, the peat surface is lowered and AWL fluctuations are transformed into smaller RWL fluctuations with a mean RWL close(r) to the surface because water is redistributed into the unsaturated zone (Ivanov, 1981; Kennedy and Price, 2005). In reverse, additional water is stored in the saturated zone when the AWL rises increasing the surface elevation and peat volume (Figure 2.1). This extra water storage increases the total storativity, which decreases fluctuations in AWL and RWL. However, gas content changes and gas ebullition have opposite effects on RWL modulation but seem to be limited to a short timescale (hours to days) (FechnerLevy and Hemond, 1996; Glaser et al., 2004; Strack et al., 2005). Moreover, OSC is suitable to express the modulation of RWL fluctuations. If the relationship between ASL and AWL is linear OSC approximates the slope of this relationship (eg. FechnerLevy and Hemond, 1996; Nuttle et al., 1990): The higher OSC, the smaller are RWL fluctuations for an equivalent fluctuation in AWL.

$$\Delta RWL = \Delta AWL - \Delta AWL \times OSC \qquad \text{(Eq 2.1)}$$

In the case of OSC=1 cm/cm (ideal flotation) all AWL fluctuations are levelled out by PSO resulting in a constant RWL. If OSC equals 0.5 cm/cm RWL fluctuations are 50% of AWL fluctuations.

Water losses eg. lateral run-off and evaporation, may also be affected by PSO. Porosity and pore size distribution are strong controls on hydraulic conductivity (Baird, 1997; Rizzuti et al., 2004; Silins and Rothwell, 1998) and drainable porosity (Letts et al., 2000). Assuming that PSO occurs as a result of changes in peat volume, ie. integrated volume of pores, hydrophysical properties such as hydraulic conductivity may vary depending on ASL. Kennedy and Price (2005) found at 2 of 3 sites hydraulic conductivity increasing by almost one order of magnitude coinciding with ASL elevated by 2-3 cm. This would increase lateral run-off for higher ASL given a sufficient hydraulic gradient. Nonetheless, PSO may significantly reduce water losses on the scale of peatlands when the peat surface ‘shelters’ the water table preventing surface run-off. Surface run-off rates exceed lateral seepage rates through peat by several orders of magnitude (Hemond, 1980; Koerselman, 1989; van der Schaaf, 1999). Furthermore, a water table below the surface reduces the probability of erosion, soil piping and the formation of gullies (Holden and Burt, 2002; Warburton et al., 2004). Many catchments with a large proportion of peatlands may accentuate floods (Bullock and Acreman, 2003; Holden, 2005; Holden and Burt, 2003; Quinton and Roulet, 1998). Most of these catchments are characterised by steep hydraulic gradients and dense peat, which implies low drainable porosity and low OSC as argued in Section 2.3. Conversely, high OSC and high drainable porosity will reduce the probability of surface run-off via reduced RWL fluctuations. We conclude that peatlands with high OSC may be systems that attenuate floods (cf. Bullock and Acreman, 2003; Edom, 2001; Holden, 2005).

In contrast, PSO could also increase water losses from a peatland through higher evaporation rates due to water tables close to the surface during dry periods. The extent of this increase remains uncertain because the role of RWL controlling in evaporation rates is not well understood (reviewed by Lafleur et al., 2005). A larger area of open water bodies (pools), however, would increase evaporation rates on the scale of a peatland because open water evaporation rates often exceed evaporation rates of peatland vegetation (Campbell and Williamson, 1997; Lafleur et al., 2005; Thompson et al., 1999). Conceivably, hydrological models addressing seasonal changes in water storage need to incorporate a transient peat surface, transient peat porosity and hence transient hydrophysical properties. All together, PSO may play an important role in promoting reduced RWL fluctuation. In landscapes with high rainfall PSO may have more effects on water table dynamics than vertical permeability gradients (ie. acrotelm concept) (Haberl et al., 2006; Lamme, 2006).

PSO is important in the restoration of mires where the re-establishment of peat-forming vegetation fails due to frequent flooding or moisture deficits. Moisture deficits are caused by drainage, compounded by the instability of water storage from the residual peat with a low drainable porosity

(Okruszko, 1995; Price et al., 2003). Studies reviewed here suggest a considerably lower potential to reduce RWL fluctuations (ie. OSC) amongst disturbed peatlands. That amplifies the desiccation of the peat forming vegetation in comparison to fairly pristine mires limiting successful restoration. Where floating peat has been available potential flooding was mitigated benefiting the establishment of peat-forming vegetation (Han and Kim, 2006; Joosten, 1995; Smolders et al., 2003).

2.6 Conclusions

The absolute surface level (ASL) in peatlands fluctuates seasonally by 1-19 cm (95% confidence interval), which is in the same order of magnitude as seasonal water storage changes (Ingram, 1983). Reversible ASL changes are called peatland surface oscillation, PSO and usually coincide with fluctuations of the absolute water level in respect to sea level (AWL). Generally, we understand PSO as a regulative function of the peat that keeps the surface close to the water table and stores extra water in saturated peat below the water table. Therefore PSO reduces fluctuations of the water table below the surface (RWL). This reduction is significant (4–100%) but variable in space and in time. PSO is driven by a set of mechanisms (compression, shrinkage, gas accumulation, freezing and flotation) rather than one uniform cause. Mechanisms may vary in the magnitude of PSO for an equivalent fluctuation in AWL. Flotation has the most thorough control on RWL fluctuations (mean reduction 63%). Measuring and predicting which mechanism (temporarily) prevails is hampered by the number of variables involved as well as the spatial heterogeneity typical for peatlands (Kennedy and Price, 2004).

Conceivably, water related studies in peatlands need to monitor both AWL and RWL. We recommend the use of a water level pressure transducer attached to a benchmark monitoring AWL and a mechanical surface level transducer, eg. pulley system, attached to the peat surface and benchmark. This design limits disturbance through frequent visits and provides high resolution monitoring. AWL and ASL can be alternatively monitored by pairing two water level transducers, one attached to the peat surface (→RWL) and one attached to a stable benchmark (→AWL). Benchmarks should be made of metal rods fixed in firm substrata and subsequent elevation surveys may confirm their stability. We regard shallow dipwells, RTK-GPS surveys and trees marked instead of the peat surface to be unreliable when compared to the range of PSO.

Hydrophysical properties that are controlled by porosity, such as hydraulic conductivity, drainable porosity and total storativity, may vary considerably following peat volume changes (PSO), which will feed back to water fluxes. Hence, hydraulic properties of peatlands vary in time and measurements of these hydrophysical parameters should be sensitive to seasonal oscillation of the surface. Besides promoting extra subsurface storage of water, PSO decreases the probability of surface run-off and thus increases the ability of peatlands to detain storm water. Measures to increase PSO (eg. lime addition increasing buoyancy via increased gas accumulation) will benefit the restoration of cutover peatlands (Smolders et al., 2002; Tomassen et al., 2003) that are characterised by seasonal water deficits and a small regulation of RWL via PSO.

Future research should concentrate on seasonal variations of PSO and spatial variability of PSO to allow for prediction to what extent the surface elevation will respond to AWL extremes. Controls on the spatial variability of PSO such as microtopography (eg. hummock, lawn), water/peat chemistry and plant cover need to be further investigated. The magnitude of PSO and impacts on hydrology in tropical and southern peatlands deserves further investigation as all but three of the reviewed studies were conducted in North America and Europe.

Chapter 3

Oscillating peat surface levels in a restiad peatland, NZ: magnitude and spatiotemporal variability

Abstract

Hydrology, particularly the water table position below the surface (relative water level, RWL), is an important control on biogeochemical and ecological processes in peatlands. The absolute surface level (ASL) in a peatland oscillates reducing RWL fluctuations. This phenomenon is called peatland surface oscillation (PSO). To investigate the spatiotemporal variability of ASL changes, RWL and the water level above sea level (AWL) were monitored continuously (one site) and monthly (23 sites) over one year in a warm-temperate restiad peatland, New Zealand. Total annual ASL fluctuations ranged from 3.2 to 28 cm (mean=14.9 cm) and were induced by AWL fluctuations (mean 40 cm among sites). The ASL-AWL relationship was linear for 15 sites. However, eight sites showed significantly higher rates of ASL changes during the wet season and thus a non-linear behaviour. We suggest flotation of upper peat layers during the wet season causing this non-linear behaviour. Total peat thickness and bulk density together could only explain 50% of the spatial variability of PSO based on manual measurements. However, we found three broad types of ASL-AWL relationships differing in shape and slope of ASL-AWL curves. These oscillation types reflected patterns in vegetation and flooding. Spatially homogenous AWL fluctuations were reduced by 30-50% by PSO except for three sites with shallow and dense peat at the peatland margin (7-11%). PSO was more subjected to hysteresis during the dry season than during the wet season. The positive ASL-AWL relationship reversed after rainfall when the surface slowly rose despite rapidly receding AWLs.

3.1 Introduction

3.1.1 Water and surface levels in peatlands

Hydrology, particularly the water table position, is an important control on biogeochemical and ecological processes in peatlands. Changes of the absolute surface level (ASL) in a peatland affect the position of the water table below the surface. Reversible ASL changes commonly range from 1 to 19 cm and have been termed peatland surface oscillation (PSO) among other terms Chapter 2. PSO is the total range of reversible ASL changes over a certain period. Processes in peatlands such as run-off (Ivanov, 1981), evaporation (Lafleur *et al.*, 2005), methane emission (Blodau, 2002; Moore *et al.*, 1998) and peat accumulation (Belyea, 1996; Blodau, 2002), for example, tend to decrease for water tables well below (>30 cm) the surface. Furthermore a review on carbon cycling in peatlands suggests that CO_2 emission rates increase with increasing water table fluctuation (Blodau, 2002). Additionally, plant species composition also depends on the water table position in peatlands (Clymo and Hayward, 1982; Kotowski *et al.,* 1998; Wierda et al., 1997).

The position of the water table itself is a function of storage changes, total storativity and surface elevation changes. Storage changes translate into water table fluctuation magnified by the total storativity, which is defined as the volume of water released from an aquifer per unit surface area per unit decline in water table in respect to sea level. Generally, the water table position can be defined in two ways (Figure 2.1): the water table position above an absolute elevation datum eg. sea level (absolute water level, AWL) and the water table depth below the surface (relative water level, RWL). The RWL indicates the thickness of the unsaturated zone including its moisture content (Barber et al., 2004; Heikurainen et al., 1964; Schlotzhauer and Price, 1999). The soil moisture content controls aeration and redox processes and thus soil chemistry (Barber et al., 2004; de Mars and Wassen, 1999). RWL has been used as a surrogate for measurements of redox and moisture state in peatland soils and is therefore the focus of green house gas and ecological studies.

Peatland surface oscillation (PSO) occurs essentially as (1) the peat volume changes (compression and shrinkage) and as (2) the peat surface floats (flotation) due to buoyancy (Chapter 2). In short, peat is very compressible on account of its fragile architecture and porosity (MacFarlane, 1965; Price *et al.*, 2005). Peat compresses when the water table recedes, as the peat matrix is no longer supported by pore water pressure, which increases effective stress in the dewatered peat layer and lower peat layers. This process is to some extent reversible. As a result, AWL fluctuations cause changes in ASL, which in turn reduce water table fluctuations in respect to the surface, because the surface ‘sticks’ to the water table. This reduction varies from 4% to 100% depending on peatland type and position across the peatland (Chapter 2). For example floating peatlands display the greatest reduction in RWL fluctuations.

Long-term irreversible subsidence takes place in peatlands when peat volume is lost by C-mineralisation and by compression/ shrinkage at rates greater than the formation of organic material. Irreversible subsidence occurs following drainage (Eggelsmann, 1978; Prus-Chacinski, 1962; Schipper and McLeod, 2002) and is exacerbated by water tables well below (<30 cm) the surface but decreases when the surface approaches the mean water table position (Schothorst, 1977).

3.1.2 spatiotemporal variability of ASL changes in the literature

Generally, a linear relationship between peat surface (ASL) and water table elevation (AWL) is suggested by a number of studies in peatlands (Baumann, 2006; Nuttle *et al.*, 1990) especially for floating peatlands (FechnerLevy and Hemond, 1996; Price and Schlotzhauer, 1999; Roulet et al., 1992; van Wirdum, 1991). A linear ASL-AWL relationship implies that the surface elevation changes proportionally to a change in AWL. Hence, the constant slope of the ASL-AWL relationship remains independent of the actual AWL position. However, there is doubt that the ASL-AWL relationship is linear in all cases. Peatland surface oscillation has been observed to cease during high AWLs (Koerselman, 1989; Swarzenski *et al.*, 1991) and low AWLs (Green and Pearson, 1968; Schwintzer, 1978; Swarzenski et al., 1991). Seasonal differences in ASL change for an equivalent fluctuation in AWL ie. a larger ASL changes in spring than in late summer, have been reported by Kennedy and Price (2005) who speculated that winter frosts increased the compressibility of peat, which then decrease during the growing season.

ASL changes are spatially variable within a peatland (eg. Gilman, 1994; Price and Schlotzhauer, 1999; Roulet, 1991; Tanneberger and Hahne, 2003; Whittington and Price, 2006). However, only a handful of studies addressed major controls on that spatial variability: Almendinger and co-workers (1986) concluded that ASL changes were related to peat thickness in a North American peatland complex and studies in temperate bogs found higher ASL changes rates in the centre than at the margin (shallow, dense peat) (Baumann, 2006; van der Schaaf, 1999). In contrast, other studies did not observe a relationship between peat thickness and ASL changes (Buell and Buell, 1941; Gilman, 1994; Price, 1994; Schwintzer, 1978). Whittington & Price (2006) observed differences of several cm in ASL changes on the scale of hummocks, lawns and hollows with presumably no significant differences in peat thickness: the lawn site showed higher ASL changes (6.5 cm) than the hummock/pool site (1 cm) being only several metres apart and subjected to the same AWL fluctuations (7.5 cm). Additionally, Holm and co-workers (2000) found surface elevation changes were inhibited when bulk density of peat increased in oligohaline fens in North America and a review of ASL changes in cutover peatlands with dense peat suggested that PSO was relatively small for an equivalent fluctuation in AWL (Chapter 2).

Wetlands dominated by restiad species are predominantly confined to New Zealand (Campbell, 1983) and PSO in these systems has not been systematically studied. Our objective was to determine the spatiotemporal variability of PSO in a restiad fen. We investigated if the relationship between water table and surface elevation is linear or seasonally variable. We also examined the relationship between PSO variability and peatland characteristics including AWL fluctuation, peat thickness, bulk density and vegetation cover.

3.2 Study area & methods

3.2.1 Study area

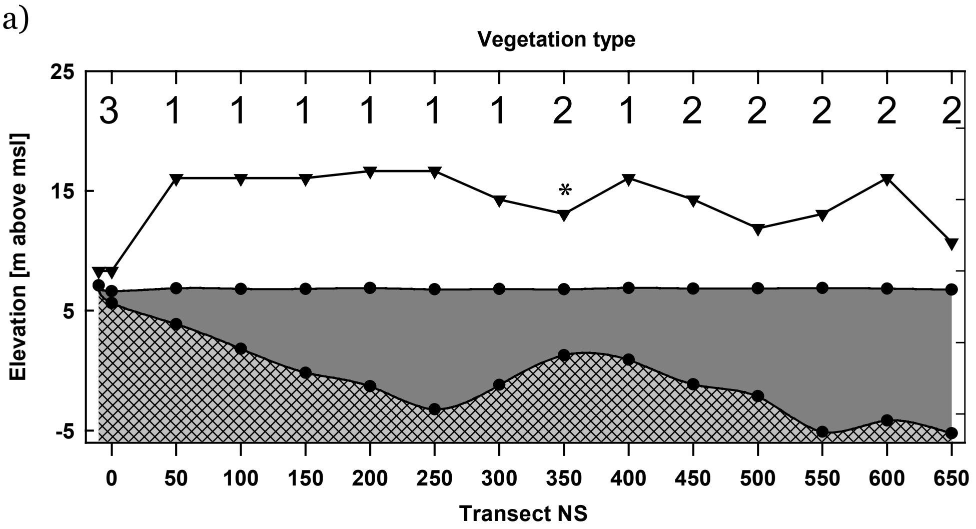
The study was conducted in a warm-temperate peatland (Opuatia wetland) 80 km south of Auckland, North Island New Zealand (37°26'S, 175°04'E). This 950 ha peatland fills a narrow valley basin next to the Opuatia River, a minor lowland tributary of the Waikato River (mean annual flow 375 m^3 s^{-1} at the closest river gauge (Environment Waikato, 2006)). Opuatia wetland is occasionally inundated with a recurrence interval of 15-30 years because of backflooding of the Waikato river as observed in 2004 (Browne, 2005). Average peat thickness was 7 m with well-preserved root peat in the upper 3.5 m underlain by highly decomposed silicate rich peats and flood deposits over impermeable clays commonly found in that region (Davoren *et al.*, 1978; Edbrooke, 2001). The peat is not drained but the surrounding hill country is used for intensive dairy farming. The 30-year average annual temperature of the closest weather station was 13.7°C with average January and July temperatures of 18.9°C and 8.9 °C, respectively (NIWA, 2006)). Mean (30 years) annual total precipitation was 1150 mm, typically with a late summer drought lasting 2-3 months.

The vegetation of large parts in the centre of the peatland is open consisting of poor fen species: restiad rushes, i.e. *Empodisma minus* (*Restionaceae*) on high relief elements (dry) and sedges, mainly *Baumea ssp.* (*Cyperaceae*), in habitats with water tables exceeding the surface. Shrubs, mostly *Leptospermum scoparium* and *Epacris pauciflora*, are scattered. The nutrient rich margins and the flood plain are dominated by trees such as introduced *Salix ssp.* and native *Leptospermum scoparium*. Moss is neither abundant in the present vegetation nor in the peat.

3.2.2 Field methods

The spatial variability of ASL changes was assessed at 23 sites 50 m apart on two perpendicular transects: The transect EW (east-west), 450 m long, bridged from dryland to dryland and transect NS (north-south) reached 650 m from margin to centre of the peatland (Figure 3.1). Peat thickness, determined using a D-Section corer (ID 4.5 cm), increased from shallow peat at the peatland's margins (<3 m) to the centre with deep peat (10-12 m) (Figure 3.1).

a)



b)

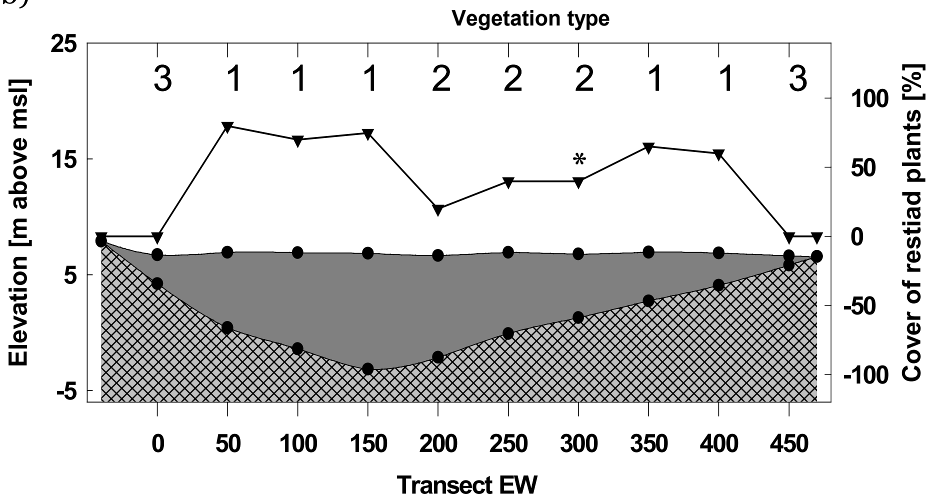


Figure 3.1: Surface elevation (upper circle), elevation of the peat base (lower circle) and cover (%) of Empodisma minus (triangle) for all sites along transect NS (a) and EW (b). Transects intersected at NS350/EW300 (asterisk). The top x-axis shows the vegetation type for each site. Sites spaced 50 m apart and GPS coordinates of the transects' ends were: NS0(N638379.6, E327104.7) → NS650 (N637788.2, E326946.3) and EW0 (N637974.5, E327330.8) → EW450 (N638065.7, E326896.8)

Every site was equipped with a benchmark consisting of a metal rod set firmly into the substratum (clay) as recommended in Chapter 2. We determined the elevation of every benchmark above mean sea level using a RTK GPS system (TRIMBLE RL 4000 & ± 3 cm horizontal accuracy). The constancy of benchmarks (±1.5 cm) was confirmed by two elevation surveys deploying a water level gauge (accuracy ±1 cm) as used by van Wirdum (1991). The peat surface was marked with a wooden plate fixed to the first 5 cm of the peat with galvanised wire and water tables were measured in slotted PVC pipes driven 1 m deep in the peat. Surface elevation (ASL) and absolute water level (AWL) data were collected monthly (August 2005–August 2006) by measuring (tape measure) the distance between benchmark and peat surface or water table, respectively. Consequently, RWL was calculated from the difference between ASL and AWL (Figure 2.1).

To describe the seasonal oscillation of ASL and AWL, high resolution vibrating wire pressure transducers (Geokon 4580-2v-2.5: 0.2 mm precision & 0.4 mm accuracy) were deployed at site NS400 (Figure 3.1) following the design of manual measurements: The transducer measuring the AWL was fixed to the metal rod and the second transducer was free to move with the peat being attached to the peat surface with a wooden board (25×18 cm) that was wired onto the fibrous peat matrix. Surface elevation changes were then calculated by subtracting RWL from AWL (Figure 2.1) so that the water table served as the relevant benchmark for every measurement. Pressure transducers were connected to a Campbell Scientific CR10X data logger to monitor water levels every 15 min. The pressure transducers were calibrated and paired in the laboratory showing no systematic differences in response. Comparing manual measurements (n=12) with data from water level transducers the standard error amounts to ±2 mm with no indication of a seasonal trend. Differences were probably caused by the combined inaccuracy of the measuring tape (±2 mm) and the water level transducers (±0.3 mm) (Appendix A).

Peat cores were collected from surface peat (0-5 cm) and standard methods were used to calculate bulk density (Blakemore et al., 1987). We estimated the canopy cover of trees, shrubs, sedges, restiad rushes and other vascular plants in units of 10% cover in plots 4×4 m.

Meteorological data (precipitation, air temperature, solar radiation, humidity) were measured at 10 s intervals with an automatic weather station and then recorded as half-hourly averages using a Campbell Scientific CR10 data logger. Assuming evaporation is relatively conservative on an annual basis, we used evapotranspiration data collected by Thornburrow (2005) using eddy covariance techniques in Opuatia wetland during 2004, sufficient for our purposes.

3.2.3 Data analysis

To describe peatland surface oscillation we calculated the ratio between total ASL range and total AWL fluctuations. This ratio is termed oscillation coefficient (OSC, Chapter 2) and is used for statistical analysis of manually measured ranges of ASL and AWL. If the ASL-AWL relationship is more-or-less linear, OSC equals the slope of the ASL-AWL curve.

To determine whether vegetation cover could explain the spatial variability of OSC we distinguished vegetation types using agglomerative hierarchical clustering of standardised (zero mean and unit variance) cover percentages of vegetation formations using the Euclidian distance as measure for similarity and Ward's method as clustering algorithm. Statistical analysis was performed with SPSS 10.0.

3.3 Results

3.3.1 Seasonal variability of water storage and ASL

Rainfall between 20th August 2005 and 20th August 2006 totalled 144.2 cm with an extended summer drought between January and April 2006 (Figure 3.2). Total rainfall in summer drought was 11.8 cm. The average air temperature was 13.5°C. Evaporation rates for 2004, ranging from 0.06-0.6 cm d^{-1}, totalled 78.7 cm (Thornburrow, 2005). Average evaporation rates (0.28 cm d^{-1}) during summer 2004 (Nov-Feb) exceeded those of the winter period (0.16 cm d^{-1}).

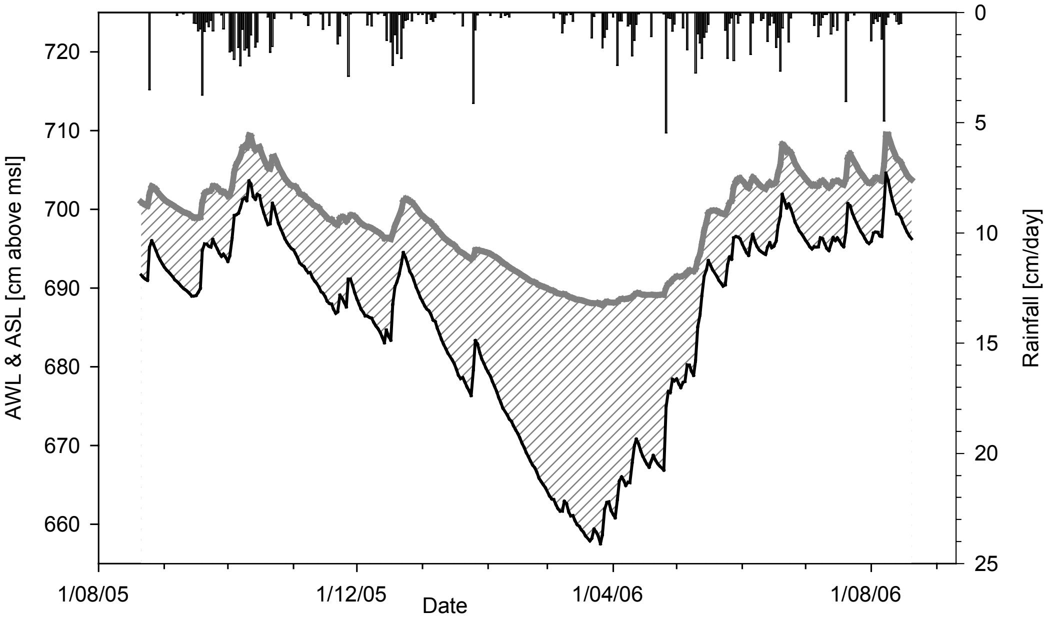


Figure 3.2: Time series of daily mean absolute water level (black line; AWL - recorded every 15 min) and absolute surface level (upper grey line; ASL) and daily rainfall sum (bars; recorded every 30 min) for a one-year period starting on 20 August 2005. The shaded region represents the unsaturated zone and its thickness equals RWL (see also Figure 2.1).

During wet seasons (June–November) ASL was strongly linked to AWL (Figure 3.2). In contrast, ASL showed little changes during and immediately after the summer drought (February–April). The rate of ASL change slowed during summer while AWL dropped sharply. The unsaturated zone (cf. RWL, shaded region in Figure 3.2) reached a maximum thickness in late summer 2006 (30.7 cm), when evaporation and run-off exceeded rainfall substantially forcing AWL to draw down. A large rise in AWL (24 cm) decreased the unsaturated zone sharply in April and May, because the surface level rose only slightly (5 cm). Conversely, the surface responded rapidly to rising AWL (10 cm) increasing some 7 cm in one week from 10 May 2006 onwards. In summary, AWL fluctuations totalled 47 cm causing 22 cm ASL changes, which reduced RWL fluctuations to 25 cm (53% of AWL fluctuations). The unsaturated zone thickness at site NS400 never decreased below 4 cm, so that the water table never exceeded the surface during the study.

The same seasonal trends can be inferred when ASL is plotted against AWL (Figure 3.3): low ASL and AWL prevailed during the dry season (lower left segment) and high ASL and AWL during the wet season (upper right segment). The relative water level is represented by the vertical distance between data points and 1:1 line. Three general types of relationships were observed between ASL and AWL (Figure 3.3): initially there was a more-or-less 1:1 relationship between ASL and AWL for AWLs above 690 cm above mean sea level (msl) common for the wet season (part ‘a’). Part ‘b’ comprises the summer drought, resulting in a continuous AWL draw down and ASL subsidence. The slope of the ASL-AWL curve decreased continually during this period approaching zero. Part ‘b’ is also very confined, suggesting a distinct ‘drying curve’. Rewetting of the upper peat started in April 2006 (part ‘c’) with a large delay of the surface elevation to rising AWL. The delayed rise of ASL prevailed until the ‘rewetting curve’ joined part ‘a’ on 16 May 2006 as a result of rapid ASL changes. To highlight the continuous character of the ‘drying curve’ an upper boundary was fitted by eye to the ASL-AWL curve using a non-linear approach: 43 % of all data is within a 0.5 cm range of the upper boundary. Remaining data points were recorded during or after rain indicating hysteresis when peat was rewetting.

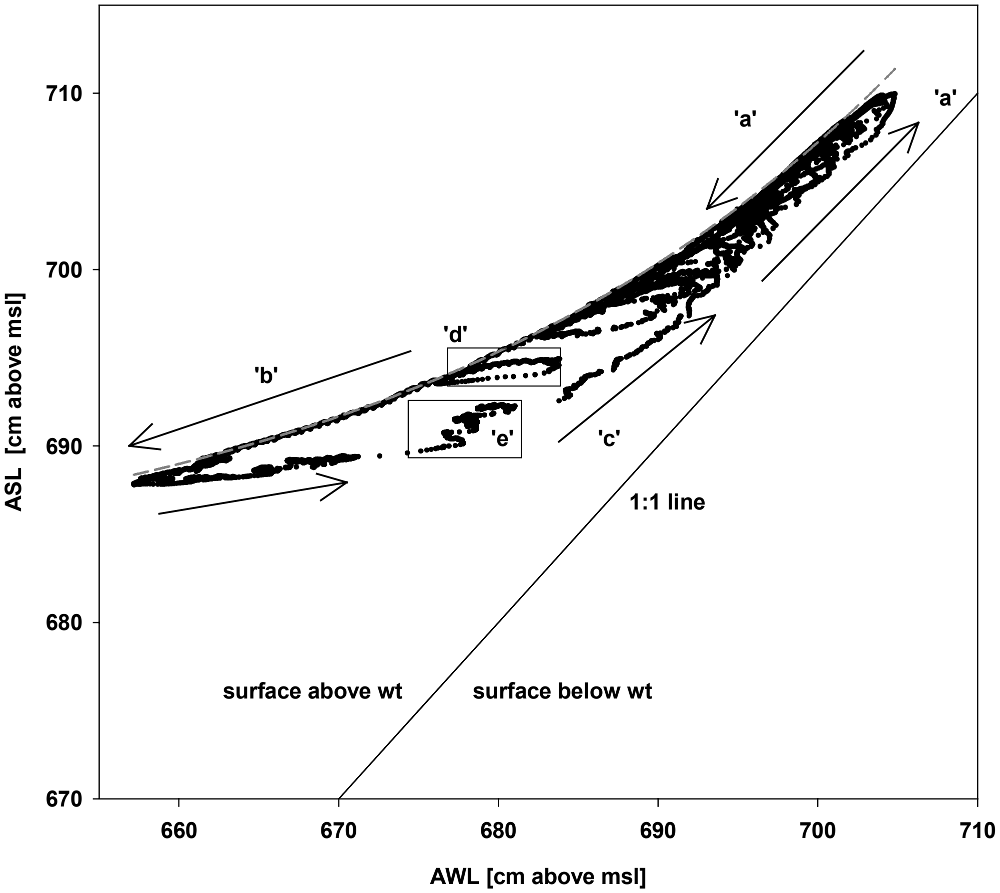


Figure 3.3: Absolute water level (AWL) plotted against absolute surface level (ASL) for a one-year period beginning 20 August 2005 comprising raw data. Measuring interval was 15 min. The vertical distance between plotted data and the 1:1 line indicates the thickness of the unsaturated zone. Note that ranges of axes differ. The upper boundary (grey dashed curve) matches with 'drying curve' (eg. part 'b') and was fitted by eye using a non-linear approach.

3.3.2 Hysteresis of ASL changes

Increasing AWL shifted the ASL-AWL relationship away from the drying curve because the response of the surface elevation to an AWL increase was delayed (Figure 3.3). Hysteresis occurred on different time scales because AWL increased during the day, during rain events (several days) and at the beginning of the wet season (Figure 3.3). Examination of one rain event in winter 2005 demonstrates hysteresis on the scale of days (Figure 3.4). Initial rainfall (3.5 cm) caused an immediate rise in AWL and ASL (Appendix C.1). However, the surface continued rising for a period of 38 hours after rainfall despite a receding AWL. During this period the ASL-AWL relationship was reversed (Figure 3.4). This delayed, hysteretic response of the surface consequently results in 'loops' in the ASL-AWL curve as the surface started rising slowly and continued rising after the AWL dropped again (eg. part ‘d’ in Figure 3.3).

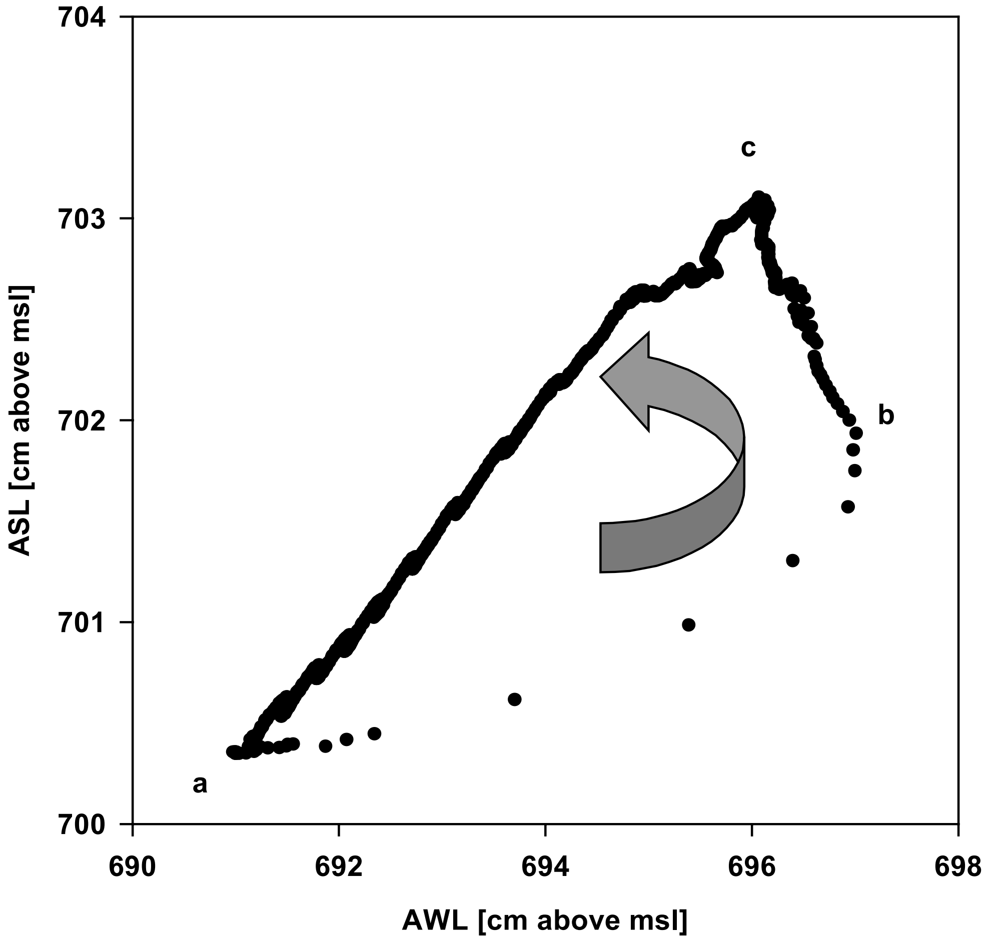


Figure 3.4: Hysteretic ASL-AWL relationship for a single rain event (3.5 cm in 6 hours) based on 15-min data (single dot). The AWL raised by some 6 cm caused an instant rise in ASL (a to b). The water table stopped rising at b. The surface rose despite AWL draw down (b to c) reversing the ASL-AWL relationship. The climax of ASL (c) was reached after some 38 h subsequent to the rain event. The ASL-AWL relationship reversed again regressing to the ‘drying curve’ exhibiting a linear relationship. First two sections (a-b, b-c) are also shown in Figure C.1.

The dataset presented here contains many of these loops (eg. part ‘d’ in Figure 3.3). Along the ‘rewetting’ curve wavy sections occurred when the water table drew down subsequent to rain events, whereas the surface level was still rising or receding very slowly (eg. part ‘e’ in Figure 3.3). Hysteresis was more pronounced during dry than wet months: drying and rewetting curves were furthest apart (13.3 cm) in the dry season (lower left segment Figure 3.3) and least (3.2 cm) for high ASL during the wet season (upper right segment in Figure 3.3).

3.3.3 Variation in AWL, ASL, vegetation and bulk density among 23 sites

Water and surface level fluctuations varied along the transects with little ASL fluctuations next to the peatland's margin and largest ranges of ASL at sites with high cover of *Empodisma minus* plants (Figure 3.1, 3.5). Maximum and minimum AWL and ASL were recorded during visits in October 2005 and in March 2006, respectively. However, three sites showed slightly lower ASL in April 2006 presumably due to hysteresis.

Total annual ASL and AWL fluctuations derived from manual measurements may be underestimated because dates of measurements and dates of extreme levels differed: At site NS400 ranges derived from the continuous record of ASL and AWL exceeded ranges calculated from manual measurements by 3 cm and 8.5 cm, respectively. AWL fluctuations averaged (±sd) 40 cm (±2.8 cm) amongst the sites and most sites (>75%) ranged within 37-43 cm (Figure 3.5). In contrast to homogeneous AWL fluctuations, ASL changes varied greatly among sites with no spatial trend (Figure 3.5). ASL changes averaged 15 cm with a higher standard deviation (±6 cm) than AWLs.

Examining the ASL-AWL relationship for all sites using manually collected data we delineated 3 broad types of relationship between AWL and ASL, which differed in shape and angle of the ASL-AWL curve (Figure 3.6). A non-linear relationship was found for type A (cf. continuous record at site NS400, Figure 3.3) with an upper slope more-or-less parallel to the 1:1 line and a lower slope approaching zero. Conversely, types B and C suggested linear relationships. Sites of type A (n=8) kept the surface above the water table. The water table exceeded the surface during high AWL at sites of type B (n=11) as a result of low OSC and a mean RWL closer to the surface than other types. Type C (n=3) comprises sites next to the dryland, where the RWL was above the surface most of the year. Type C sites showed little changes in ASL (below 6 cm) and thus, very small OSC. However, this classification failed to fit site NS250 that showed highest ASL changes

(Figure 3.5) but a linear ASL-AWL relationship (Figure 3.7). Site NS250 also showed the highest OSC (0.74) among sites.

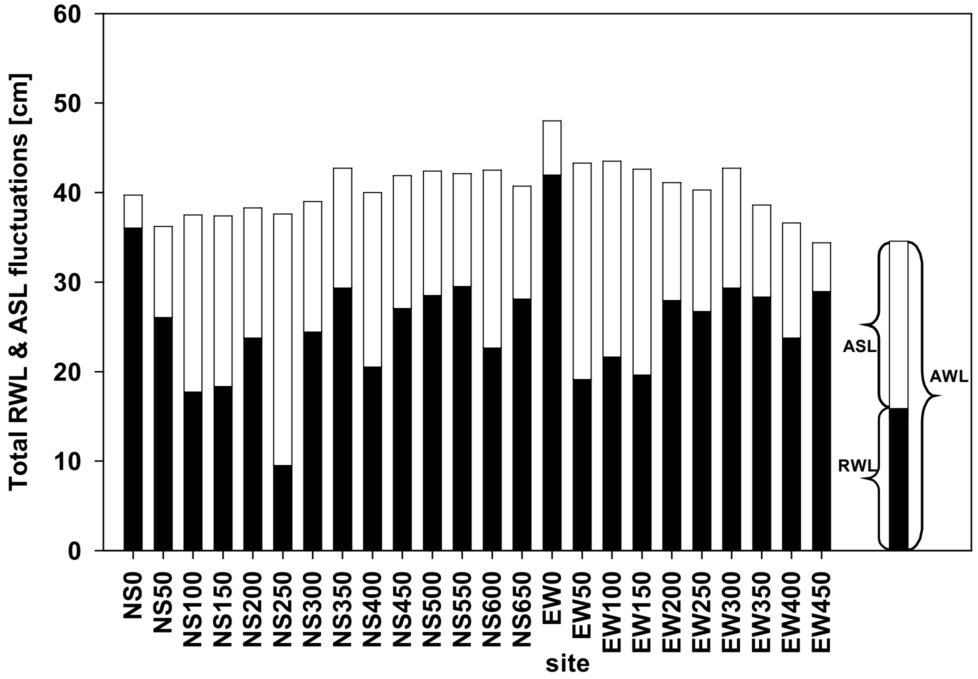


Figure 3.5: Spatial variability of total fluctuations of, relative water level (RWL, black bars), absolute surface level (ASL – white bars) and absolute water level (AWL– sum of both bars) based on manual measurements. Maximum and minimum levels were recorded for all but three sites in October 2005 and March 2006, respectively. At site EW450 the sum of RWL and ASL fluctuations exceeds directly measured AWL fluctuations by 1.8 cm.

Oscillation types were also distinct in regard to total RWL fluctuations, which were spatially variable despite relatively homogenous AWL fluctuations (Figure 3.5). RWL fluctuations at type A sites (mean 20 cm) were less than 24 cm, but the RWL fluctuated more than 24 cm at type B (mean 27 cm) and type C sites (mean 36 cm). Water tables were at least 2 cm below the surface for all sites in summer. Wet season water tables were close to or above the surface for most sites. However, some sites (NS250, NS400, EW100, EW150) sustained an unsaturated zone exceeding 4 cm throughout the year, which may have implications for plant growth.

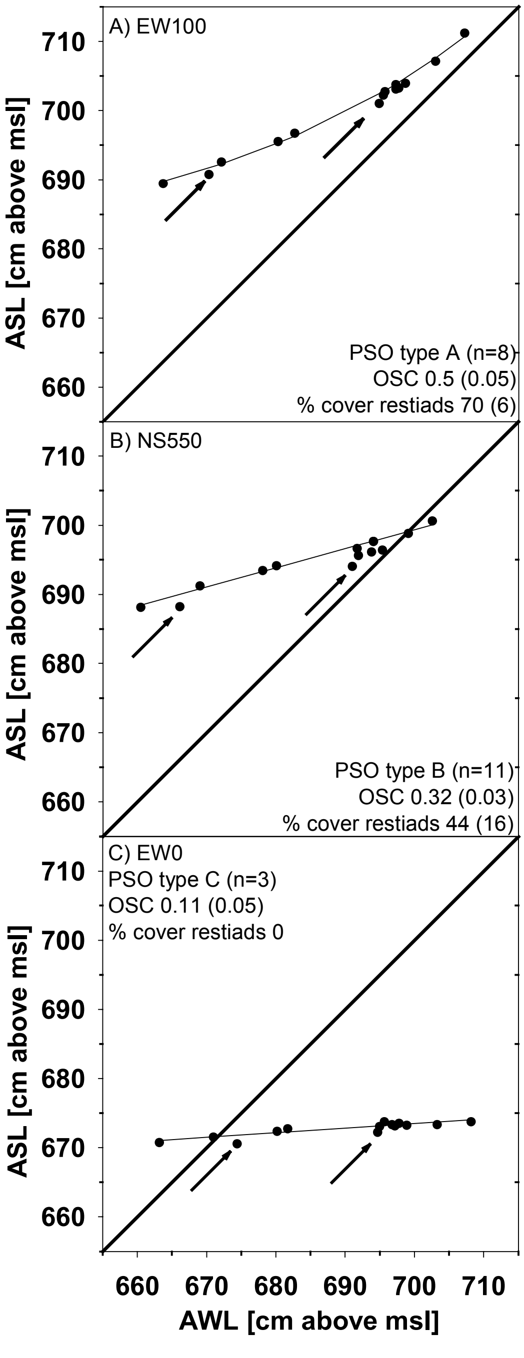


Figure 3.6: Spatial variability of the ASL-AWL relationships among sites. Each graph represents an oscillation type (A-C). Type criteria are slope shape and angle of the ASL-AWL curve. OSC is the ratio between total range of ASL changes and total range of AWL changes and is presented here as the mean (sd) of sites per type. Also for every type the mean (sd) percentage cover of restiads ie. *Empodisma minus* is provided. Solid lines represent regression models based on measurements on days (n=8), where data points are close to the drying curve on Figure 3.3. Diagonal lines are 1:1. Arrows point to measurements taken in April (left) and May 2006 (right) revealing hysteretic behaviour of PSO.

Vegetation at the 23 sites can be grouped in to three vegetation types showing some spatial trend. Restiads (>60% cover) were abundant in type one, which dominated the northern half of transect NS and was also abundant on transect EW (Figure 3.1). Vegetation type two was characterised by a higher sedge cover (>20% cover) and the abundance of shrubs. Most of the vegetation type two sites concentrated on the southern half of transect NS. Vegetation type three was dominated by high growing trees as well as shrubs and was limited to sites at the nutrient rich margins. There was a close match between vegetation types and oscillation types. For example all sites of oscillation type A (cf. a non-linear ASL-AWL relationship) belonged to vegetation type one, ie. high cover of restiads. Vegetation type two sites belonged exclusively to oscillation type B (except for NS300) with a mean water table close or above the surface (Figure 3.6). Oscillation type C was restricted to margins that were dominated by type three vegetation.

Bulk density averaged (range) 0.09 (0.05 –0.18) g cm^{-3} and showed no spatial trend except for sites next to the dryland exceeding 0.1 g cm^{-3} (data not shown).

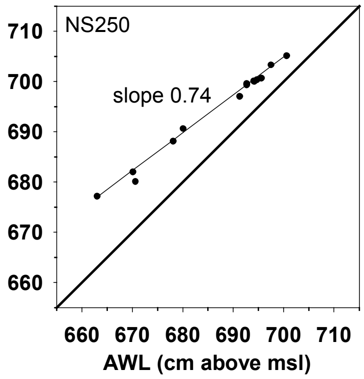


Figure 3.7: ASL-AWL relationship close to 1:1 as recorded by manual measurements at site NS250, which was omitted in the classification of sites (cf. Figure 3.6). The solid line represents a regression model based on measurements on days (n=8), where data points are close to the drying curve on Figure 3.3.

3.4 Discussion

3.4.1 Non-linearity of ASL-AWL relationship & hysteresis

A linear relationship between absolute water level (AWL) and absolute surface level (ASL) in peatlands has been suggested (eg. Nuttle and Hemond, 1988; Price and Schlotzhauer, 1999) particularly for floating peatlands (FechnerLevy and Hemond, 1996; Koerselman, 1989; Roulet, 1991; Roulet et al., 1992). The peat surface level in Opuatia wetland oscillated continuously following AWL fluctuations during the study without cessation as reported for other peatlands by Green and Pearson (1968), Koerselman (1989) and Swarzenski et alii (1991). Automatic and manual measurements support a close ASL-AWL relationship for all sites indicating reversible ASL changes, hence peatland surface oscillation (PSO). However the ASL-AWL relationship was non-linear for 35% of the sites (Figure 3.3; Figure 3.6). In the case of non-linearity PSO was large during the wet season for the equivalent fluctuation in AWL resulting in a reduction of RWL fluctuations of up to 80% compared to the dry season. Therefore, the absolute position of the water table (AWL) controlled PSO and the slope of the ASL-AWL relationship was non-linear.

The magnitude of ASL changes (cf. OSC) may depend on the prevailing PSO mechanism. For example flotation results in substantially higher ASL changes for the equivalent fluctuation in AWL than compression or shrinkage of peat (eg. Roulet, 1991). Therefore, seasonal shifts between mechanisms would then result in non-linear ASL-AWL curves. The slope of the ASL-AWL curve at site NS400 (‘drying curve’ in Figure 3.3) differed substantially at low AWLs (0.2) and high AWLs (0.8). We suggest that at times of highly fluctuating ASL upper peat layers were almost floating and thus flotation was the main cause of PSO. Conversely, low ASL fluctuations were recorded when mainly compression and shrinkage (or any other mechanism but not flotation) may have caused PSO. Sites belonging to oscillation type B and C, ie. linear ASL-AWL relationship, showed less PSO presumably due to a lack of flotation. Additionally, site NS250 could not be encompassed by any oscillation type because of the steep slope (0.74) of the linear ASL-AWL curve (Figure 3.7). The outstandingly large PSO at this site may have resulted from a floating-like behaviour that was not temporally limited to high AWL during the wet season.

To find a distinct layer of water (cf. water cushion), which allows flotation, the peat profile at site NS400 was investigated during the wet season in 2005. No explicit layer of free water was found. However, the peat between 50-150 cm was very soft and compressible indicating high moisture content. Temporary flotation implies that upper peat layers are subjected to grounding and lifting, which has been only described for floating peatlands comprising large water bodies in the peat profile (Green and Pearson, 1968; Schwintzer, 1978; Swan and Gill, 1970; Swarzenski et al., 1991; van Wirdum, 1991). Temporary flotation has not been reported yet for non-floating systems. A study of ASL changes in a cutover bog in Canada suggest also a seasonally variable slope of the ASL-AWL relationship but did not consider temporary flotation as a cause (Kennedy and Price, 2005). Kennedy and Price (2005) speculated that winter frosts increased the compressibility of peat and thus the potential for PSO. However, hysteresis of PSO or subsidence was not considered.

We conclude that the concept of a floating peatland is only applicable for a defined range of space and time. In other words, floating peatlands can cease flotation, whereas the surface peat in ‘fens’ and ‘bogs’ may temporally float. In order to estimate the proportion between flotation and peat volume changes (compression/shrinkage) causing ASL changes it is necessary to measure elevation changes of peat layers at various depth (Eggelsmann, 1981; Gilman, 1994; Price, 2003).

The non-linearity of the ASL-AWL relationship impacts the accuracy of models that predict the hydrological response of peatlands to lower AWL, which may be caused by human impact on peatlands or changing weather patterns: Roulet and co-workers (1992) predicted a ~22-28 cm AWL draw down for a northern boreal peatland under a $2 \times CO_2$ climate scenario. They assumed that an increase of the unsaturated zone would be continuously mitigated by 50% due to ASL changes (OSC= 0.5). Manual measurements reported here suggest that the majority of sites may exhibit a linear ASL-AWL relationship but with varying slopes. However, our continuous dataset strongly suggests that a linear model eg. a linear regression through the ‘drying curve’, slope = 0.46, substantially deviates from observed ASL/RWL (cf. Figure 4.6). This linear model overestimates ASL changes and the reduction of RWL fluctuations by up to 135% for low AWL. Conversely, ASL changes are underestimated for high AWL. Therefore, extrapolation and generalisation of sparse manual measurements (limited frequency or observation period) are prone to errors. Non-linear behaviour should always be considered to be a possibility. Future models of hydrological response to climate change should also incorporate changes in hydraulic parameters such as porosity and permeability resulting from ASL changes (Camporese et al., 2006; Kennedy and Price, 2004; Kennedy and Price, 2005).

3.4.2 Hysteresis of peatland surface oscillation

A hysteretic response of the surface elevation to AWL changes was found on all time scales (seasonally, episodically and daily) during continuous monitoring (Figure 3.3, 3.4). Manual measurements also indicate that PSO was seasonally hysteretic for most sites (Figure 3.6). However, hysteresis was less obvious because of the paucity of manual measurements during the rapid rewetting phase (Figure 3.6). Eggelsmann (1981) also reported hysteresis of ASL changes (total 20 cm) in a drained peatland that lasted for several months subsequent to rapid lowering (200 cm) and subsequent to rapid recovery of AWL (200 cm) six months later. Generally, the main drivers of ASL changes, moisture movement and peat porosity, show hysteretic behaviour (Heikurainen et al., 1964; Naasz et al., 2005; Price and Schlotzhauer, 1999; Schindler et al., 2003; Schwärzel et al., 2002; Tsuboya et al., 2001). We speculate that cause, ie. AWL changes, alter the effective stress (as defined by Terzaghi (1943)) and effect, ie. structural changes in peat volume induced by effective stress (eg. Hobbs, 1986; Kennedy and Price, 2005), operate on different time scales. Water level fluctuations occur in the range of minutes to hours but it may take hours to days until forces imposed on the peat matrix equilibrate. Also, the spatial variability of PSO rates may cause horizontal drag on the peat matrix that requires time to be evened out. The extent of hysteresis may depend on the main mechanism forcing the surface to oscillate. For example, hysteresis was striking for low AWLs, when ASL changes occurred presumably only due to compression/shrinkage (Figure 3.3). In contrast, hysteresis was minor during the wet season, when the peat appeared to be floating (Figure 3.3). No hysteretic behaviour of the surface elevation was reported from a free floating peatland in the USA (FechnerLevy and Hemond, 1996). We hypothesise that ideal flotation (no lateral or horizontal drag) results in non-hysteretic ASL changes. The ASL-AWL relationship would then be parallel to the 1:1 line assuming no changes in buoyancy of the peat. Clearly, water and surface level monitoring need to adjust to this hysteretic behaviour eg. higher measuring frequency subsequent to large rain events and ‘outliers’ need to be treated with care.

3.4.3 spatial variability of PSO and controls

Annual surface elevation changes of all sites were reversible, which is a defining criterion for peatland surface oscillation (PSO). We monitored PSO larger (10-28 cm) than values reported for fens (0.4-10 cm) except for three marginal sites with little PSO (Chapter 2). This may result from high AWL fluctuations (mean 40 cm). Also, high OSC values (≥0.5 for 8 of 23 sites) are close to the mean OSC (0.63) reported for floating peatlands (Chapter 2), which furthermore supports our hypothesis that ASL changes of these sites are partly due to flotation.

Generally, PSO was found to be spatially variable. Results of this study support a positive relationship between peat thickness and PSO as hypothesised by Almendinger and co-workers (1986), but this relationship was weak ($r^2=0.27$, $p<0.05$). Peat thickness and bulk density explained together less than 50% of spatial variation in PSO. In contrast, the cover of the restiad plant *Empodisma minus* explained a substantial part of the spatial variability ($r^2=0.65$, $p<0.001$). Additionally, the cover of *Empodisma minus*, peat thickness and bulk density explained 73% of the spatial variability. However, all three variables were likely autocorrelated and true drivers of spatial variability of PSO are difficult to determine.

We observed OSC to be higher in central parts than at the peatland's margin (Figure 3.5), as reported elsewhere (Baumann, 2006; Holm et al., 2000; Price, 1994; Tanneberger and Hahne, 2003; Touber, 1973; van der Schaaf, 1999). Measurements of elevation changes in individual peat layers in northern hemisphere peatlands suggest that ASL changes are confined to the upper 1 to 1.5 m of peat (Gilman, 1994; Price, 2003). Thus, we suggest that only a limited part of the peat profile contributes substantially to surface elevation changes by compression/shrinkage. As thickness of this crucial part of the peat body may not have varied significantly, the control of peat thickness on ASL changes became overwritten by other peatland variables such as vegetation.

3.5 Implications for the water-plant relationship in peatlands

The mean position and fluctuation of the water table below the surface controls the composition of dominant plants (eg. Clymo and Hayward, 1982; Ivanov, 1981; Kotowski et al., 1998; Wheeler and Shaw, 1995; Wierda et al., 1997). Despite relatively homogenous AWL fluctuations (Figure 3.5) there was a significant site-to-site variation in RWL position and fluctuations as well as vegetation. RWL fluctuations were controlled by the oscillation coefficient (OSC in Eq. 2.1). Spatially variable OSC would cause site-to-site variations of RWL fluctuations resulting in various water level regimes, which favour different plant communities. Consequently, sites of oscillation type A, ie. high OSC, should have a very small probability of inundation because RWL fluctuations would be mitigated by flotation, whereas types B & C sites may be inundated, which was found in Opuatia wetland.

The frequency of water tables above the surface may control the vegetation at Opuatia wetland. *Empodisma minus*, a dominant peat former (Campbell, 1983) and the only restiad species in the study area, grows on high (dry) relief elements avoiding full saturation of the root zone (Johnson and Brooke, 1998). *Empodisma* plants form a dense matrix of highly specialised cluster roots in the first 7-10 cm of the peat that consists of living, gas filled tissue (aerenchyma) (Agnew et al., 1993; Campbell, 1964; Neumann and Martinoia, 2002). Fertilisation experiments using ^{15}N isotopes indicate that nutrient uptake occurs in the upper 5 cm of the root matrix (Clarkson, 2005). The high percentage cover of *Empodisma* plants at sites with large PSO suggested that *Empodisma* plants benefited from the reduction of inundation and RWL fluctuations (Figure 3.6). More specifically, flotation prevented the complete saturation of the root zone (cf. Figure 3.2, 3.3, 3.6). Hogg & Wein (1988a) showed that the root system of *Typha ssp.* can contributed up to 20% of the buoyancy within the root zone raising the surface level of floating mats in North American wetlands. Further investigation is required to determine whether *Empodisma minus* can engineer its environment via flotation given the high volume of gas filled plant tissue in the near surface peat.

3.6 Conclusion

We reported the magnitude of peatland surface oscillation (PSO) measured for one year in a warm temperate restiad peatland that is little affected by human activities. The surface level (ASL) oscillated by 10-28 cm for 20 of 23 sites, which is in the upper range of reported values for peatlands. PSO was controlled by the absolute elevation of the water table (AWL) and PSO reduced fluctuations of the water table below the surface (RWL) by 30-50% for 19 of 23 sites. It was discovered that the relationship between ASL and AWL was not uniform due to hysteresis, which occurred at a number of time scales after a rise of the AWL. Delayed adjustment of the peat matrix to changes in effective stress may cause this hysteresis. Also, for 35% of 23 sites the ASL-AWL relationship was non-linear: PSO was up to four times higher during high AWLs than during low AWLs for the equivalent fluctuation in AWL. Therefore, the increase of the unsaturated zone during the dry season was proportionally larger compared to the wet season. We propose a switch in PSO mechanism (compression → flotation) to cause this non-linear behaviour. Hydrological monitoring and modelling need to allow for an oscillating surface because differences between AWL and RWL can be substantial. Otherwise, calculated water balances or RWL dynamics may be wrongly interpreted depending on the differences between AWL and RWL dynamics. Although a linear approach facilitates a simple approximation of the ASL-AWL relationship, hysteresis and non-linearity need to be considered.

Peatland surface oscillation is important for ecological processes. The site-to-site variability of RWL fluctuations and thus peatland plant species composition is controlled by PSO if AWL fluctuations are homogenous. Floating peat rafts can be applied, where restoration of peatlands is hampered due to flooding (Money, 1995; Schipper *et al.*, 2002). Further investigation is needed to determine to what extend plant species feed back to PSO. The control of PSO on drainable porosity and hydraulic conductivity needs to be quantified, when the temporal variability of these hydraulic parameters would be incorporated in hydrological models.

Chapter 4

This chapter extends the discussion of Chapters two and three. It is considered whether plants can affect PSO. The interaction between PSO and important hydraulic characteristics such as drainable porosity, total storativity and hydraulic conductivity is further discussed, continuing Section 2.5.

4.1. Plants controlling ASL changes

Empodisma minus, and other peatland plants, may actively promote peatland surface oscillation as suggested in Chapter 3. The implications of plant induced surface oscillation are discussed here for restiad peatlands in the Waikato. The key argument is that plants can decrease the wet bulk density of peat under water logged conditions by storing gas in underground organs. A decrease of wet bulk density to less than the density of water may promote flotation, which is a very effective mechanism causing peatland surface oscillation. Phytogenic flotation was first described by Kulczynski (1949, pp. 297-307), who called it 'dysaptic structure' (of peat).

4.1.1 Gas content in peat and buoyancy

Buoyancy forces of gases and solids is an important component in the equilibrium of forces imposed on the peat matrix (Ivanov, 1981; Kennedy and Price, 2005; Stegmann et al., 2001). In brief, buoyancy ceases when peat becomes unsaturated ie. water table draws down. The loss of buoyancy transfers the weight of the unsaturated peat (water, solids and gas) onto underlying layers. This weight is supported by the water body under waterlogged conditions. The stronger the buoyancy forces of a saturated peat layer, the differences in weight ie. effective stress this peat layer imposes on underlying peat when unsaturated. Hence, buoyancy of uppermost peat result in larger compression of peat layers underneath, when the uppermost peat dewaters in comparison to peat with no buoyancy. Peat with a wet bulk density less than 1 g cm^{-3} pulls upwards stretching the peat matrix when no loading is imposed from above. Peat less dense than water floats if detached from underlying substrate.

Small changes in gas content have large consequences for wet bulk density of peat ie. buoyancy forces Figure 4.1. Surprisingly small gas contents in peat can promote flotation. Gas in peat originates from biochemical processes mainly driven by microorganisms (cf. methanogenesis, denitrification, respiration) and from gas in underground tissues of plants either transported down through the plant or formed in situ. To compute the effect of volumetric gas content on wet bulk density a gas mixture comprising constant 50% N_2 and 50% CH_4 with an average density of 0.95 10^{-3} g cm^{-3} is assumed. The density of a gas mix similar to atmospheric conditions (80% N_2 and 20% O_2) is slightly higher, 1.23 10^{-3} g cm^{-3}. Peat particle density is assumed to be 1.5 g cm^{-3} , which is similar to densities found in a restiad peatland (Whangamarino wetland) 20 km east of Opuatia wetland (Hodge, 2002).

A gas content of only 2-4 vol. % is sufficient to result in buoyancy of peat with a dry bulk density ranging from 0.05 and 0.1 g cm^{-3} (Figure 4.1). This range of dry bulk density was found in the surface peat (0-5 cm) for 20 of 23 sites in Opuatia wetland (Chapter 3). Sites close to the peatland margins had dry bulk density above 0.1 g cm^{-3}, which would require a gas content of 5-8 vol. % to cause buoyancy (Figure 4.1).

Gas contents recorded in peatland soils commonly exceeded 5 vol. % (review in Kellner *et al.*, 2005). However, only a limited number of peatlands may be characterised by flotation: A density slightly smaller than 1 g cm^{-3} may not create buoyancy forces strong enough to overcome the tensile stress of the peat matrix in order to separate peat layers. Separated uppermost peat is more likely to float than the entire peat body because deeper peat is more compacted and more decomposed, with a higher mineral content, resulting in a higher wet bulk density (Clymo, 1983; Clymo *et al.*, 1998; Newnham *et al.*, 1995).

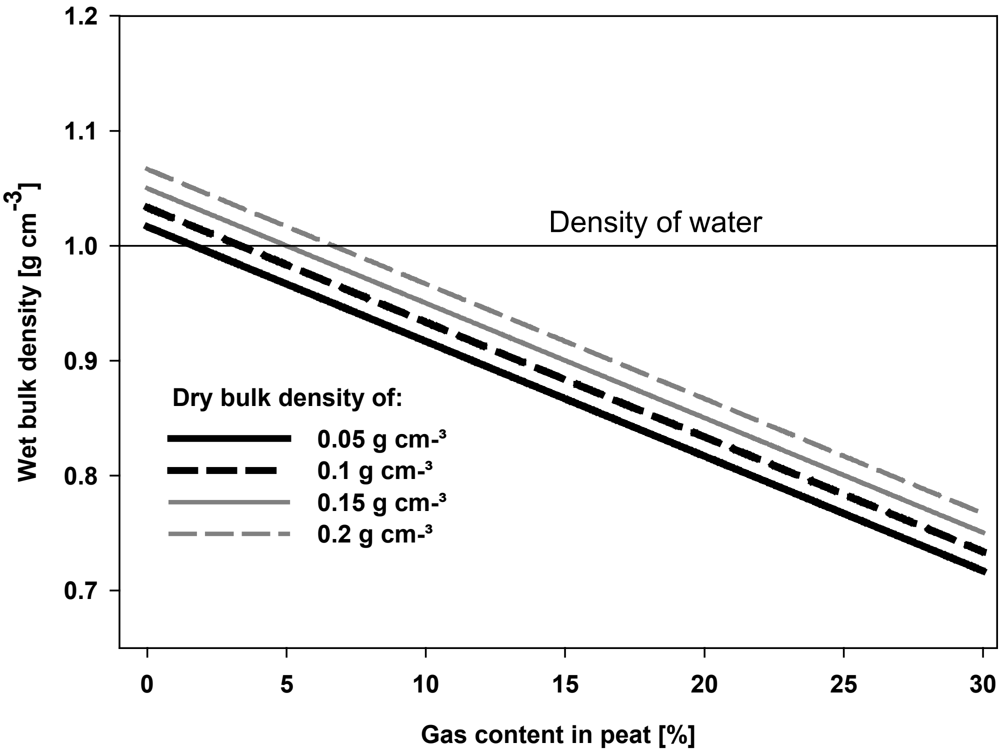


Figure 4.1: Dependency of wet bulk density (buoyancy) on gas content in peat plotted for different dry bulk densities ranging from 0.05 g cm^{-3} to 0.2 g cm^{-3}. Particle density of the peat is assumed to be 1.5 g cm^{-3}. The density of water is 1 g cm^{-3} and peat less dense than 1 g cm^{-3} is buoyant.

4.1.2 Plants may control buoyancy of upper peat layers

Wetland plants actively transport oxygen in their root systems to raise the redox potential of the root environment and mediate toxic conditions (Crawford, 1983; Mainiero, 2006; Neumann and Martinoia, 2002; Sculthorpe, 1967; Sorrell et al., 2001). The underground plant organs of wetland plants may contain more than 50 vol. % of gas conducting tissue, aerenchyma (Campbell, 1964; Mainiero and Kazda, 2005; Sorrell et al., 2001). Therefore, plant controlled gas content in upper peat layers can be substantial if related to the total gas content in peat (Hogg and Wein, 1988a; Mainiero and Kazda, 2005).

Empodisma minus forms high amounts of upgrowing roots in the first 7-10 cm of the peat (Agnew et al., 1993; Campbell, 1964; Campbell, 1975)(Figure 4.2). Campbell (1964) estimated that underground organs of *Empodisma* contain 25-50% gas filled voids (aerenchyma). My field observations and preliminary lab experiments suggest that the upper 30 cm of peat of some restiad mires (eg. Opuatia, Kopouatai, Whangamarino in the Waikato and Bayswater Swamp and Shearer Swamp in lowlands of the South Island, New Zealand) floats when separated from the underlying highly compressible root peat, commonly 50-100 cm thick.

Figure 4.2: Cluster roots of *Empodisma minus*. Photo by E.W.E. Butcher.

It may be the roots of *Empodisma* plants that add enough buoyancy to the peat to detach upper peat layers resulting in temporary flotation. Flotation results in large PSO compared to AWL fluctuation (Chapter 2). High ranges of PSO in Opuatia wetland were found presumably due to flotation of upper peat layers (Chapter 3). Sites that may have been floating showed also a high cover (>60%) of *Empodisma* (Figures 3.6, 3.7). However, the trend of high PSO coinciding with high cover percentage of *Empodisma* was not uniform along the transects. Three other sites also had a high cover percentage of *Empodisma,* but did not show any indications of temporary flotation. These sites were within 150 m of the peatland margins and the peat profile (0-100 cm) was more decomposed (>H5 after Von Post scale) and seemed to be more compacted than central sites (cf. Figure 3.1). The relationship between *Empodisma* cover and oscillation coefficient (r^2=0.65, p<0.001, n=23, Chapter 3) loses strength in a partial correlation that controls for peat thickness and bulk density (r^2=0.44, p<0.001, n=23). Therefore, the strength of the relationship between plant cover and PSO depends on the location of the two transects and if sites next to the peatland margin are included in the dataset (0% *Empodisma* cover and little PSO but also shallow peat with a high dry bulk density). In the case of the three marginal sites shallow and dense peat may have limited PSO rather than the lack of *Empodisma* plants. This highlights that abiotic factors also control the spatial variability of PSO besides vegetation. Also, the cover % of above ground vegetation may insufficiently indicate density and thickness of underground plant organs.

Shrubs, eg. *Leptospermum scoparium*, can develop a vast root mass rich in aerenchyma under waterlogged conditions (Cook *et al.*, 1980). Monitoring of AWL and ASL in 2003/2004 by Browne (2005) (her sites '10' & '11' showed practically no RWL fluctuations) revealed high rates of ASL changes (OSC>0.7) and low AWL fluctuations (some 10 cm) in *L. scoparium* dominated parts, at the north end of Opuatia wetland. Hence, *L. scoparium* may also have potential to control ASL changes in peatlands. Floating systems that are dominated by shrubs (eg. *Chamaedaphne calyculata*) have been described for mires in North America (Hemond, 1980; Kratz and DeWitt, 1986; Swan and Gill, 1970). However, all these relationships are speculative. Phytogenic buoyancy and its impacts on water table dynamics and PSO requires further investigation.

4.1.3 Implications of vegetation-controlled ASL changes for peatlands in the Waikato

Plants may influence surface oscillation in peatlands and thus, vegetation dynamics may have implications for peatland hydrology beyond variant evaporation rates (Campbell and Williamson, 1997; Eggelsmann, 1981). For the past 100 years peatlands in the Waikato, including large areas of restiad peatlands, have been subjected to invasion of exotic plants, most prominently the swamp species *Salix cinera* and *Salix fragilis* (Browne, 2005; Clarkson *et al.*, 2002). When *Empodisma minus* dominated communities are out-competed by *Salix ssp.*, *Empodisma*'s underground organs die back resulting in a mean surface level lowered by 20-30 cm. This is supported by several observations:

- living parts of *Empodisma* are found to a large extent in the uppermost peat (0-50 cm) (Agnew et al., 1993; Campbell, 1964; Campbell, 1975).
- at the sharp transition between invading *Salix ssp.* and *Empodisma* dominated areas at Opuatia, hummocks of *Empodisma* were patchy and decreased in size and number towards *Salix ssp.* dominated areas. Plants appeared unwell indicating a die back of *Empodisma* presumably due to shading (field observation).
- The surface elevation of sites with little cover of *Empodisma* was at least 20 cm below the average ASL of the peat surface along the two transects (Table F.1).

The loss of extensive root mass may cause a substantial loss of buoyancy and hence a loss of ASL oscillation. As a result AWL fluctuations would be hardly mitigated by ASL oscillation. The mean RWL would presumably exceed the surface. All together, the invasion of *Salix ssp.* may create swamp like conditions (highly fluctuating RWL above the surface) that consequently favour swamp species such as *Salix ssp.* This positive feedback can promote further infestation. The thorough infestation of swamp species and subsequently changes in water table dynamics of an entire peatland would sharply increase surface run-off. This increase in surface run-off would be caused by water tables above the surface because run-off would not be slowed down by the low permeability of peat (relative to above ground vegetation). Thus, valuable peatland functions such as water storage and flood attenuation may become inhibited. Detailed hydrological monitoring should investigate the nature of water fluxes at the sharp transition between *Salix* and *Empodisma* dominated communities.

4.2. Implications of PSO for hydrological self-regulation of peatlands

In this section the importance of PSO for water fluxes in peatlands is explored. The mutual relationship between surface level dynamics, water table dynamics and hydraulic characteristics are discussed with the help of a flow chart (Figure 4.3). Furthermore, an oscillating surface limits RWL fluctuations controlling biogeochemical processes such as carbon and nutrient dynamics and species assemblage. The magnitude of reduced RWL fluctuation is discussed using a simple model.

4.2.1 Importance of drainable porosity, PSO and hydraulic conductivity on peatland hydrology

Peat volume changes feed back to water table dynamics via hydraulic conductivity, drainable porosity, total storativity and compression (Figure 4.3). The relationships presented here are based on a conceptual model compiled by Couwenberg and Joosten (1999), that is extended by incorporating PSO. The effects of the water table position on evaporation rates are not considered.

Drainable porosity is central in translating storage changes into AWL fluctuations: the higher the drainable porosity, the smaller are AWL fluctuations for an equivalent change in storage. As an example, if the drainable porosity is 0.2, a 2 cm storage change will result in 10 cm AWL change. If the drainable porosity is 0.5 , a 2 cm storage change translates into only 4 cm AWL fluctuation. Total storativity, which is the sum of drainable porosity and dilation coefficient, is considered below.

Peat decomposition progresses with time reducing drainable porosity and carbon content of the peat. Pore and carbon losses increase peat bulk density. Moreover, decomposition rates can vary. Aerobic decomposition exceeds anaerobic decomposition by several order of magnitude (Belyea, 1996; Kuder et al., 1998; Williams and Yavitt, 2003). The deeper the mean water table below the surface, the longer a peat layer above the water table is exposed to aerobic decomposition. In other words, mean RWL of -15 cm below the surface exposes peat on average 150 years to aerobic decomposition given a mean AWL rise of 10 cm/100 years (cf. peat accumulation rates in Belyea and Clymo, 2001; Clymo et al., 1998;

Newnham et al., 1995). In contrast, a mean RWL of -5 cm below the surface exposes peat for only 50 years to aerobic decomposition under the same assumptions. In a similar way to drainable porosity, hydraulic conductivity depends mostly on the volume of large cavities (pores) in peat (Baird, 1997; Rizzuti *et al.*, 2004). Decrease in (large) pore volume means less run-off through the peat body and thus a decrease of water losses. If this negative feedback loop prevails further water losses are regulated and hence further increase of the unsaturated zone is limited (Couwenberg and Joosten, 1999; Joosten and Clarke, 2002).

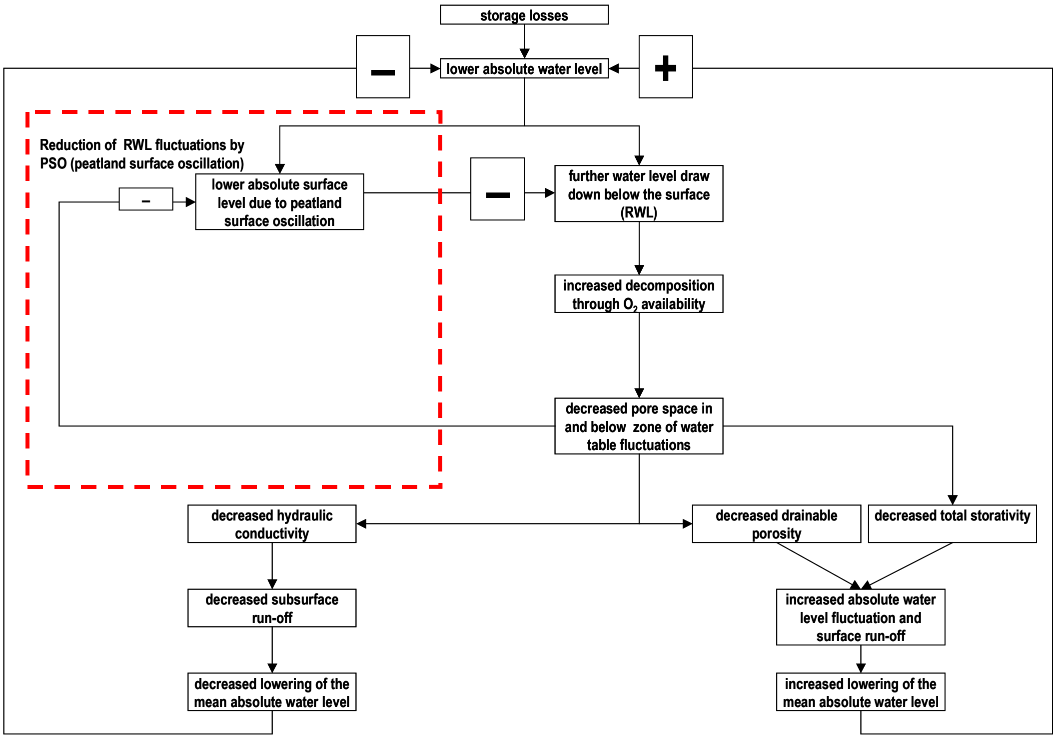


Figure 4.3: Positive and negative feedback between water table and hydraulic characteristics in a system consisting of organic matter (eg. peatlands and marshes) and having significant lateral water flow (adapted from Couwenberg and Joosten, 1999). Negative feedback loops through peatland surface oscillation are highlighted by dashed box.

PSO also has regulative effects on water fluxes. Most prominently, PSO reduces RWL fluctuations (see below and Chapters 2 and 3). Water tables are closer to the surface because the surface follows water level fluctuations. PSO also increases the total storativity by providing extra storage of water below the water table. Peat volume changes result predominantly results from water content changes and not from changes in mass or particle density of solid matter. The amount of surface oscillation due to compression and flotation results from additionally stored water in the peat matrix and thus equals the additional storage provided by PSO. (In rigid aquifers only the pores adjacent to the water table are filled or emptied subsequent to storage changes, whereas in compressible aquifers like peat all pores across the entire aquifer thickness respond to storages changes like a sponge. The peat body seems to respire following storage changes. Because of a transient pore volume PSO has also been termed 'mire breathing' (Ingram, 1983)).

However, the regulative role of PSO may be limited. Firstly, PSO can be non-linear (Figures 3.3, 3.6 and B.1). The lower the water table, the smaller the mitigating effect on water table dynamics. The magnitude of this decrease is further discussed in Section 4.3. Secondly, PSO resulting from peat volume changes may significantly alter drainable porosity and total storativity (cf. Chapter 1.2). In the case of a lower surface, water table dynamics may be amplified due to a decrease in drainable porosity and total storativity (ie. dilation coefficient, see Section 1.2). Conceivably, the decrease in drainable porosity depends on the position of volume changes along the peat profile. Volume changes in peat layers below the zone of water table fluctuation can not cause changes in drainable porosity but will feed back to total storativity (Ivanov, 1981; van der Schaaf, 1999) and hydraulic conductivity (Chow et al., 1992; Kennedy and Price, 2005; Whittington and Price, 2006). Decreasing the peat volume increases bulk density, which has been associated with smaller amounts of compressibility and PSO due to compression (Hobbs, 1986; Price et al., 2005; van der Schaaf, 1999; Whittington and Price, 2006). However, a substantial decrease PSO would probably require a large compaction (Kennedy and Price, 2005). For example, the majority of sites in Opuatia wetland exhibited a linear ASL-AWL relationship so no negative feedback loop between peat volume and PSO. Non-linearity (ie. oscillation type A) may have been caused by a switch between PSO mechanisms (flotation → compression), which can only be indirectly related to peat volume changes. Section 3.3.

Finally, any pore volume loss is counteracted by peat forming vegetation refurnishing the system with highly porous substrate (Clymo, 1983; Couwenberg and Joosten, 1999). The pore volume appears to be central in controlling hydrological characteristics such as hydraulic conductivity and drainable porosity. Extending Figure 4.3 by including production rates of porous substrate would add a factor compensating pore volume losses. For example fresh peat may provide high drainable porosities and enough pores that can compress or store gas promoting PSO. Therefore, peat formation is vital to maintain the regulative functioning of PSO for water fluxes in peatlands (cf. Joosten, 1993). Biomass production may also benefit from a stable hydrological regime, which stresses the importance of PSO that directly mitigates RWL draw down. In warm temperate mires PSO and large biomass production (above- and underground) may have a larger control on water table dynamics than vertical gradients in hydraulic conductivity (ie. acrotelm concept) by providing substrate with high drainable porosities and with a high potential for PSO (Haberl et al., 2006; Kahrmann and Haberl, 2005; King, 1999; Lamme, 2006).

Conclusively, PSO feeds back to water table dynamics in peatlands by reducing RWL fluctuations through surface elevation changes and increasing the total storativity. However, the efficiency of PSO in regulating water fluxes may be limited in time because continued water losses do not increase PSO. In contrast, annual peat formation replenishes the pore volume in the uppermost peat promoting potential for high PSO.

4.2.2 Simulating the influence of ASL change rates on RWL fluctuations and water storage above the surface

In this section a series of simple simulations is used to show how the magnitude of peatland surface oscillation (PSO) is important for peatland hydrology. Reducing RWL fluctuation may be the most prominent effect of PSO on water fluxes in peatlands. To calculate RWL fluctuations and ASL oscillation Eq 4.1 and Eq 4.2 are applied assuming a linear ASL-AWL relationship with negligible hysteresis:

$$\Delta ASL = OSC \times \Delta AWL \qquad \text{Eq. 4.1}$$

$$\Delta RWL = \Delta AWL - \Delta ASL \qquad \text{Eq. 4.2}$$

Absolute water level fluctuation (ΔAWL) causes an oscillation of the absolute surface level (ΔASL) to an extent that is proportional to the oscillation coefficient (OSC, Chapter 3). The oscillation of the absolute surface level reduces overall fluctuations of the water level (ΔAWL), which consequently reduces RWL fluctuations (ΔRWL in Eq. 4.2).

AWL fluctuations monitored for site NS400 were used for all simulations. These fluctuations may be representative for all sites (except EW450) as argued in Chapter 3. For example, at site EW150 an automatic monitoring site was set up deploying two water level pressure transducers (Instrument Services & Developments SS3 and SS1, Figure A.2). The set-up of the probes was identical to the set-up discussed in Section 3.2. Comparing continuous records at sites NS400 and EW150 (160 m apart) indicate mean deviations of ± 1.5 cm (Figure 4.4). Homogenous AWL fluctuations may be simply explained by exceptionally high hydraulic conductivity of the upper 100 cm of peat (10^{-4}–10^{-2} m/s) in large parts of Opuatia wetland as estimated by slug tests (data not shown) using standard methods (Baird *et al.*, 2004; van der Schaaf, 1999). These values are in the upper end of conductivities reported in literature but similar to findings of King (1999) for Kopouatai peat bog.

RWL dynamics as simulated could feed back to AWL dynamics as fluctuations occur in depth with a drainable porosity that is variable with depth. More sophisticated simulations would need to consider this relationship. Also manipulating PSO and mean RWL may impact water fluxes as argued before. However, PSO and mean RWL varied largely along the transects causing little spatial variation of AWL (Figure 3.5, Appendix F.1). Therefore, simulations of RWL fluctuations by manipulating OSC in a simple model (Eq 4.1, 4.2) are advisably interpreted on the scale of a single site although patterns and trends may be valid on the scale of a peatland.

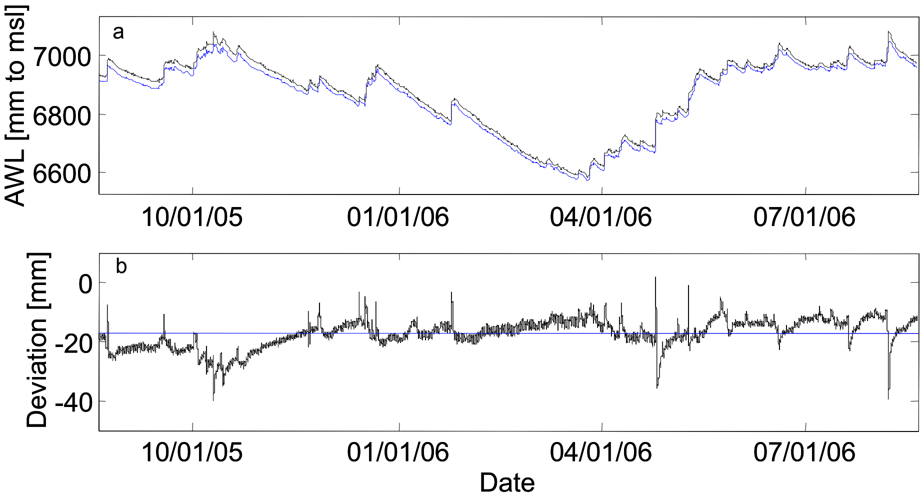


Figure 4.4: a. AWL dynamics at site NS 400 (lower solid line) and EW150. Upper black solid line based on 15-min level monitoring using water level pressure transducers; b. The difference between AWL fluctuations at the two sites revealed little deviation (± 15 mm). The offset between was -17 mm (horizontal line) due to the hydraulic gradient in Opuatia wetland.

Negligible PSO (OSC= 0 cm/cm) means that AWL translates 1:1 into RWL fluctuation, which is generally assumed in water level monitoring in mineral soils (Figure 4.5a). Raising OSC to 0.1 cm/cm shows little influence on RWL fluctuations (Figure 4.5b). The water table would be close to or above the surface over a large proportion of the year, whereas water tables up to 40 cm below would be possible (frequency chart in Figure 4.5a-b). This compares well with results from my field study: RWL fluctuated largely at marginal sites (NS0, EW0, EW450) with OSC < 0.11 and water tables above the surface were observed frequently (Chapter 3). Conversely, OSC values of 0.3 and 0.5 reduce RWL fluctuations significantly (Figure 4.5c-4.5d). The frequency charts appear to be more compact. However, OSC below 0.5 (cm/cm) allows for water tables above the surface occasionally. At sites of oscillation type A (mean OSC=0.50) the surface remained above the water table throughout the study. Occasional flooding was found at sites of oscillation type B (mean OSC 0.32). The proportion of these events depends on the starting position of RWL (see below). A OSC of 0.8 leaves less than 10 cm RWL fluctuations and the frequency chart is very compact (Figure 4.5e). The surface seems to be almost floating in this case. A similar behaviour was observed at site

NS250 with little RWL fluctuations (9.6 cm, Figure 3.7). Very stable RWL and RWL slightly below the surface promote high plant productivity and high peat formation, which would be achieved under this scenario despite AWL fluctuations of some 50 cm. If the mean RWL is shifted up to 4 cm below the surface (averaged mean RWL of sites with oscillation type B), water tables are above the surface for approximately 50% of the time (Figure 4.5f). Such frequently high RWLs would permit huge losses of water via surface run-off, when maintained on the scale of a peatland.

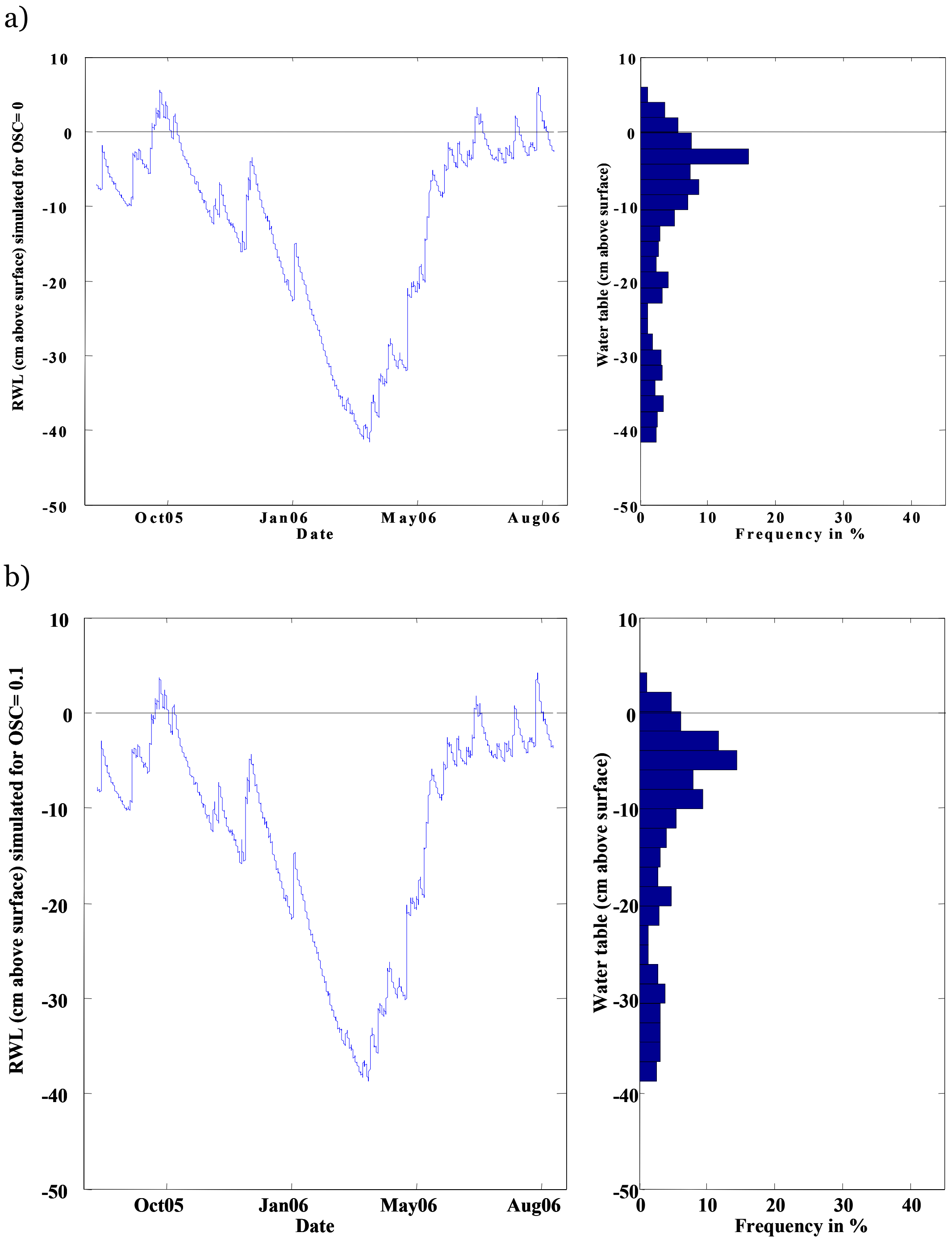


Figure 4.5 (part I): Simulations of the water table position above the surface (solid black line) depending on differing oscillation coefficients (a. 0.0 and b. 0.1). Mean RWL was -12.8 cm. The bar graph (right) shows the frequency of the water table position. Bar thickness is equivalent to 2 cm along the peat profile.

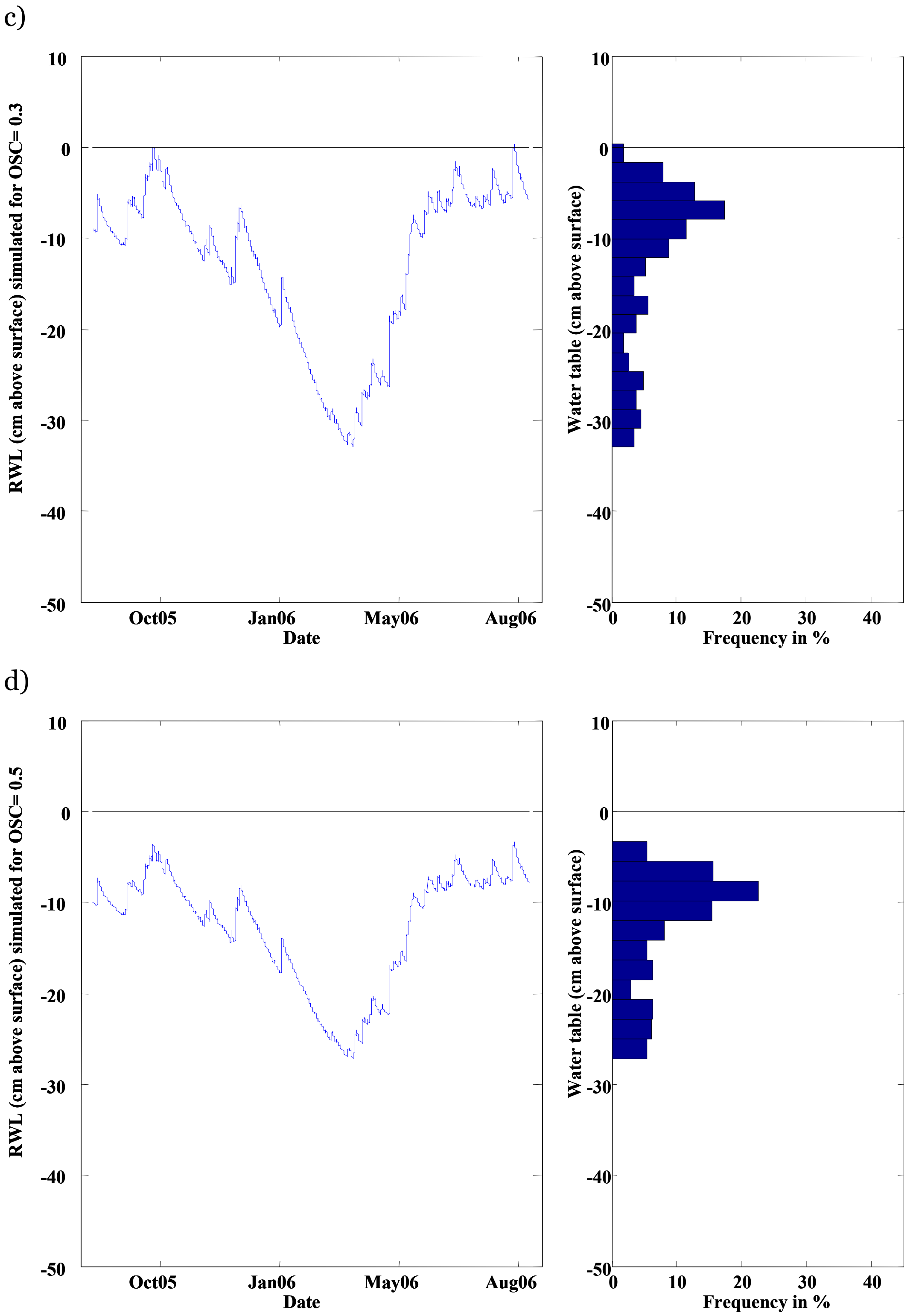


Figure 4.5 (part II): Simulations of the water table position above the surface (horizontal black line) depending on differing oscillation coefficients (a. 0.3 and b. 0.5). Mean RWL was -12.8 cm. The bar graph (right) shows the frequency of the water table position. Bar thickness is equivalent to 2 cm along the peat profile.

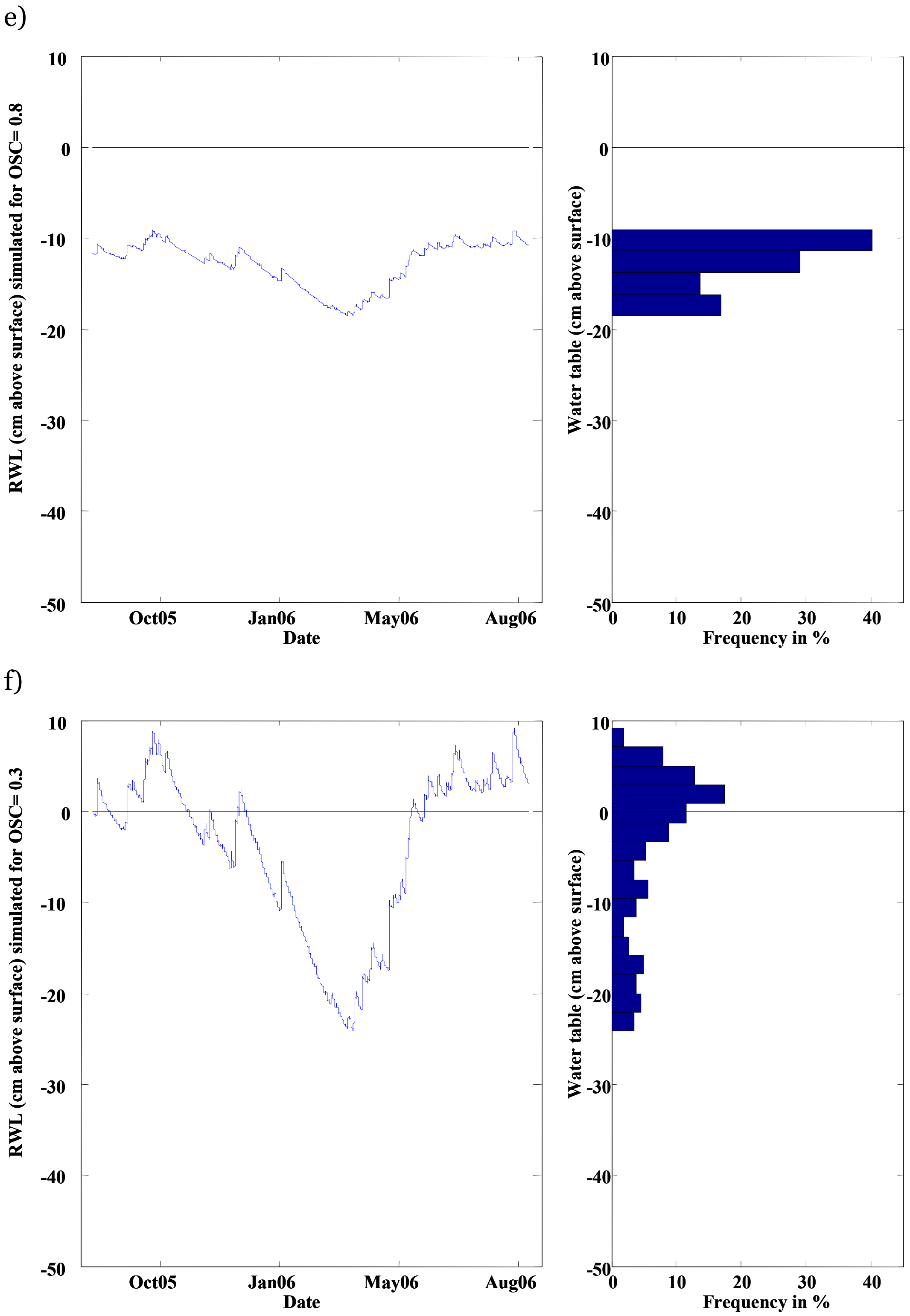


Figure 4.5 (part III): Simulations of the water table position above the surface (horizontal black line) depending on differing oscillation coefficients (e. 0.8 and f. 0.3). Mean RWL was -12.8 cm in e and –4 cm in f. The bar graph (right) shows the frequency of the water table position. Bar thickness is equivalent to 2 cm along the peat profile.

A finding of the literature review suggests that OSC of 0.2-0.4 seems to be the common range for 'fens' and 'bogs' (Chapter 2). Lower values were often recorded at margins of peatlands or in peatlands with mineral rich peat. The latter would imply a high bulk density. OSC values in Opuatia wetland ranged between 0.2-0.4 cm/cm for more than 50% of 23 sites. In this range RWL fluctuations are significantly reduced as shown above. However, water tables exceeding the surface may be frequent depending on the mean RWL, which is a function of the microrelief.

In order to demonstrate to what extent reduced RWL links back to storage changes a simple calculation follows. Assumed are annual AWL fluctuations of 40 cm and a drainable porosity averaging 0.3 that is constant over time in the uppermost 50 cm of peat. Drainable porosity values of 0.3 were also assumed by Letts et al. (2000), who reviewed hydraulic parameters of peatlands in the northern hemisphere.

Hence, storage changes equal -12 cm, which could result from ~40 days with negligible rainfall, mean evaporation rates of 0.25 cm d^{-1} and 0.05 cm d^{-1} run-off) Assuming a fixed surface RWL fluctuations would amount to 40 cm. In contrast, an oscillating surface reduce RWL fluctuations. Presuming a OSC range of 0.2-0.4 AWL fluctuations would be translated to RWL fluctuations of 32 to 24 cm according to Equations (4.1 and 4.2). Without an oscillating surface storage changes would need to decrease significantly by 22-44% to create similarly reduced RWL fluctuation. In other words, any run-off would need to be inhibited (~20% water losses) or evaporation rates needed to be halved. It seems that an oscillating surface is also an important means besides reduced evaporation (Campbell and Williamson, 1997) and run-off (Ivanov, 1981) to create stable water tables (Figure 4.3).

Conclusively, peatland surface oscillation is important in creating different water table regimes over very small distances (Figure 4.5 a-e) and reducing water losses on a peatland scale by decreasing the probability of surface run-off (Figure 4.5e). This can be important for peat accumulating peatlands (mires as defined by Joosten and Clarke, 2002). Mires face the following dilemma: water tables close to the surface promote high peat accumulation rates by suppressing aerobic decomposition of peat. However, high water tables can cause substantial water losses depleting water storage through surface run-off. High oscillation coefficients, on the other hand, stabilise water table dynamics, even when water tables are just below the surface.

4.3 Implications of non-linearity of the ASL-AWL relationship for hydrological models

The discussion in Chapter 3 highlighted that a linear model is unsuitable to predict ASL in the case of a non-linear ASL-AWL relationship. Here the discussion continues by predicting ASL changes for AWL draw down beyond AWLs recorded during 2005/2006. In that case RWL fluctuation may be underestimated substantially using a linear model. Non-linearity may result in a switch from a stable hydrological regime to a highly dynamic hydrological regime for a water level draw down beyond a certain level (Figure 3.3). Campbell and Jackson (2004) described such switches for peatlands in the Waikato.

Assumed is an AWL draw down of 30 cm, so that results can be compared with Roulet *et al.* (1992), who predicted a ~22-28 cm lower AWL for a northern boreal peatland under a $2 \times CO_2$ climate scenario (increase in temperature and precipitation of 3 °C and 1 mm d^{-1}, respectively (Mitchell, 1989)). To validate differences between a non-linear and a linear model at site NS400 ASL was predicted using an exponential model (cf. upper boundary in Figure 3.3) and alternatively using a linear regression through the 'drying curve' (slope=0.46), respectively (Figure 4.6). Models were implemented using Matlab 6.1 (MathWorks). The parameters for the exponential model were derived from the best fit of four data points equally spaced by hand on the 'drying curve'.

For AWL receding 0.30 m below 6.57 m above msl the linear ASL-AWL model may overestimate the subsidence of the surface by 0.12 m. Hence, the linear model would underestimate the draw down of the water level below the surface by 40% of the AWL draw down when compared to the non-linear model. In other words, the more the water table recedes, the lesser is the reduction of RWL fluctuation through PSO using an exponential model.

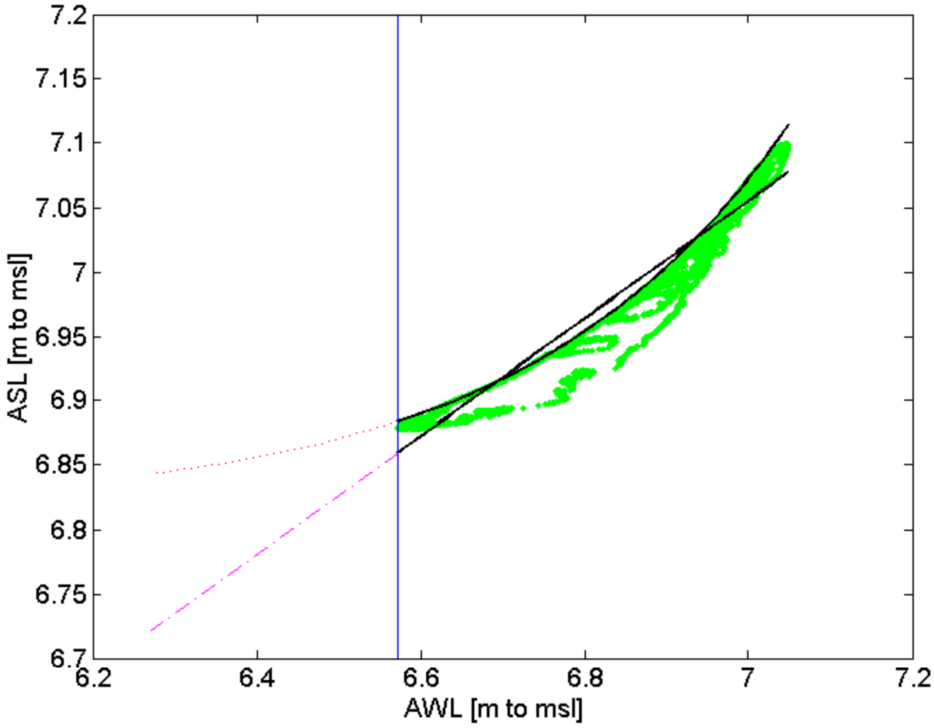


Figure 4.6: Extrapolation of ASL changes (y-axis) from AWL draw down (x-axis) 0.3 m beyond 6.57 m above msl. Models were based on ASL-AWL 15-minute data as collected at site NS400 from August 2005 to August 2006 (cf. Figure 3.2 and 3.3). Dotted line (red) is the extrapolation of the 'drying curve' (cf. Figure 3.3). The line below (dash dots purple) is the linear regression model through the 'drying curve'. The difference (0.12 m) between the models at AWL equalling 6.27 m above msl (=0.3 m below lowest AWL in 2006) is discussed in the text. Recorded data are right of solid vertical line (AWL 6.57 m above msl).

A sharp decrease of ASL changes are common in floating peatlands due to grounding of the floating mat as shown earlier (Chapter 2). Therefore ASL-AWL models in floating peatlands need to consider a sharp decline in ASL changes per equivalent fluctuation in AWL and thus non-linearity. Even if the ASL-AWL relationship is linear (PSO is not triggered by flotation), ASL changes may decrease in magnitude as peat becomes increasingly compacted limiting further compression as argued in Section 4.2.1. However, Eggelsmann (1981) reported continued ASL changes (in total 20 cm) after an immense AWL draw down (200 cm) indicating that PSO may decrease in magnitude but does not completely cease even in very dry periods.

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Appendix A

Appendix A concerns the accuracy and precision of absolute water level (AWL), relative water level (RWL) and of absolute surface level (ASL) monitoring. Uncertainties of ASL measurements are the focus. Firstly two error models are presented, one for automatic measurements using water level transducers and a second one for manual measurements using measuring tape. Error estimations are provided for datasets including the continuous record of AWL and ASL at site NS400 (Chapter 3) and two additional sites (EW150, NS100), which are briefly discussed in Appendix B.

RWL is by definition the distance from ASL to AWL (Figure 2.1) and thus it can be calculated by subtracting ASL from AWL (Eq. A.1; all three variables are directly related to each other). Therefore, in order to monitor water levels and the surface level in peatlands, only two variables need to be measured as the third can be calculated by rearranging Eq. A.1.

$$RWL = AWL - ASL \qquad \text{Eq.A.1}$$

Continuous monitoring of ASL used this relationship so that only RWL and AWL were measured using water level transducers (Chapter 3). ASL can then be calculated rearranging Eq.A.1.

$$ASL = AWL - RWL \qquad \text{Eq.A.2}$$

Hence, errors of ASL measurements result from the combined uncertainties in measuring AWL and RWL since these measurements contain uncertainties (E_{AWL} and E_{RWL}). The uncertainties of AWL and RWL measurements derive from the limited precision and inaccuracy of the water level transducers deployed. The resultant uncertainties of ASL measurements (RE_{ASL_auto}) can be calculated using Eq.A.3 (Watts and Halliwell, 1996).

$$RE_{ASL\_auto} = \sqrt{\left(E_{AWL\_auto}{}^{2} + E_{RWL\_auto}{}^{2}\right)} \qquad \text{Eq.A.3}$$

In contrast, AWL and ASL were measured directly when manually monitored. Hence, RE_{ASL_manu} equals E_{ASL_manu}. Uncertainties of measurements using a measuring tape under field conditions are at least ±2 mm.

To compare automatic measurements against manual measurements of ASL and AWL the difference between both measurements was calculated (ΔASL). An ideal match between both types of measurements would leave a difference of zero. However, this close match is unlikely as both types of measurement incorporate uncertainties. Hence the resultant uncertainties of $RE_{\Delta ASL}$ need to be considered:

$$RE_{\Delta ASL} = \sqrt{\left(RE_{ASL\_auto}{}^{2} + RE_{ASL\_manu}{}^{2}\right)} \qquad \text{Eq.A.4}$$

During the field study manual measurements were taken only by the author using the same measuring tape so that RE_{ASL_manu} is assumed to be constant (±2 mm). The continuous dataset of AWL and ASL in Chapter 3 was measured with two vibrating wire pressure transducers (Geokon 4580-2v-2.5 & 0.2 mm precision) at site NS400. RE_{ASL_auto} for this site amounts to ±0.3 mm using Eq.A.3.

This section also discusses uncertainties of measurements at two additional sites: pressure transducers of the type Instrument Services & Developments SS3 and SS1 (henceforth ISD pressure transducer) were deployed at site EW150 with a precision of ±1.5 mm and ±2.5 mm, respectively. E_{ASL_auto} at site EW150 amounts to ±2.9 mm using Eq.A.3. At site NS100 two 1.5 m long Odyssey capacitance probes with a precision of ±7 mm were deployed. E_{ASL_auto} for NS100 amounts to ±9.9 mm using Eq.A.3.

Calculating RE_{ASL_auto} for every set of probes already suggests that the most accurate dataset was collected at site NS400. Differences between manual measurements and automatic measurements of ASL at site NS400 are small (Figure A.1). The standard error of ΔASL measurements (n=12) amounted to ±2.3 mm, which is within the range of uncertainty, when comparing manual with automatic measurements ($RE_{\Delta ASL}$= ±2.0 mm using Eq.A.4). The precision of Geokon vibrating wire pressure transducers probes is sub-mm. The pressure transducers were calibrated and paired in the laboratory showing no systematic differences in response. Similarly, ΔASL showed no seasonal drift. Hence, I conclude that the Geokon vibrating wire pressure transducers are appropriate for measuring ASL changes and for interpreting small-scale patterns as evident from Figure 3.3.

Differences between manual measurements and automatic measurements of ASL at site EW150 (Figure A.2) exceed differences reported for site NS400. The standard error of ΔASL amounted to ±8.9 mm, which is larger than the combined uncertainty of measurements ($RE_{\Delta ASL}$= ± 3.5 mm). The increasing deviation between manual measurements and ISD pressure transducer data suggests a drift in the second half of the monitoring period. The drift appeared to result from errors of the probe measuring RWL (Figure A.2) because the error of the probe measuring AWL remains fairly constant over the monitoring period and revealed a smaller standard error (±5 mm). The drift may be a result of instrument errors as it is limited to one device. Data collected by ISD pressure transducers has to be treated with care.

Differences between manual measurements and automatic measurements of ASL were largest at site NS100 (Figure A.3). The standard error of ΔASL amounted to ±10.0 mm, which matches well with the uncertainty that derives from comparing different measuring techniques ($RE_{\Delta ASL}$= ± 10.1 mm). However, Odyssey capacitance probes revealed large errors during low AWLs in the summer season (cf. Figure B.2 & E.2). These large deviations clearly affect the shape of the AWL-ASL curve (B.2). Capacitance probes generally develop a film on their measuring device (capacitor) that mimics higher water levels. The development of films is strongest during periods of slowly receding water levels and in waters that are rich in substances that precipitate when oxidised (in Opuatia mainly iron and manganese species and dissolved organic carbon). Therefore, the

RWL probe underestimated substantially the distance between the water table and surface after prolonged drying. Odyssey capacitance probes may not be suitable to provide an accurate record of ASL dynamics stretching over several seasons.

In summary, different types and makes of water level transducers revealed substantial differences in accuracy that limit their application. Geokon vibrating wire pressure transducers appeared to be very reliable and stable. In contrast, ISD pressure transducers drifted seasonally and Odyssey capacitance probes seemed to be affected by water quality, which increased the inaccuracy. Very precise vibrating wire pressure transducers are recommended for high resolution long-term monitoring of ASL dynamics. Less accurate pressure transducers suit most purposes of ASL monitoring given that probes do not drift. Odyssey capacitance probes are capable to provide estimates of ASL dynamic and range of ASL changes.

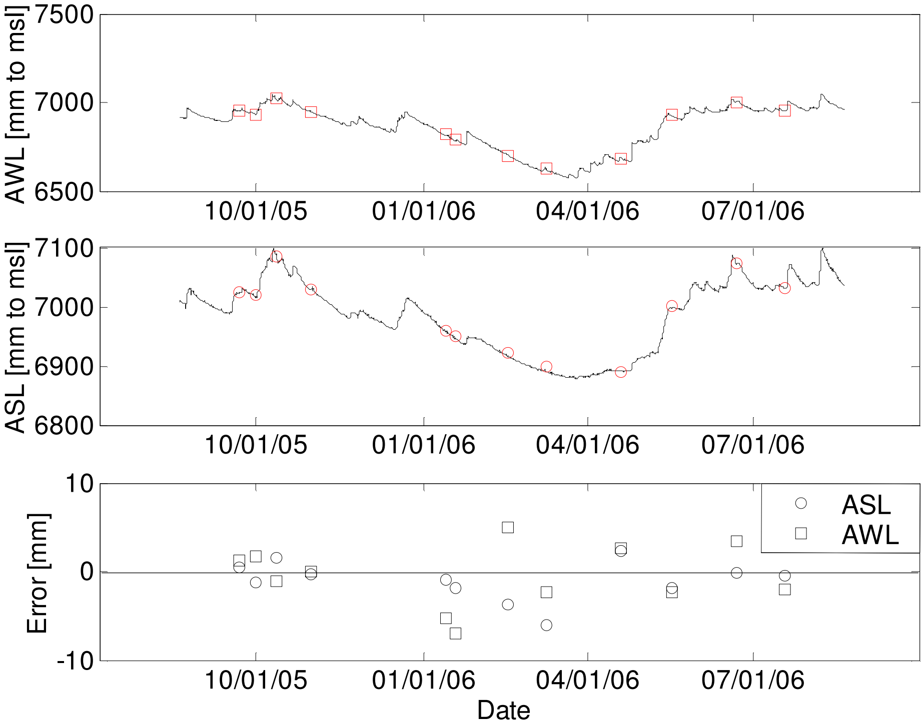

Figure A.1: Comparison between manual measurements (n=12) and automatic water level transducers at site NS400. Upper graph shows AWL (solid line) and manual measurements (squares). Middle graph shows ASL (solid line) and manual measurements (circles). Lowest graph shows the deviation between automatic and manual measurements: Deviation for AWL measurements and ASL measurements is shown by squares and circles, respectively.

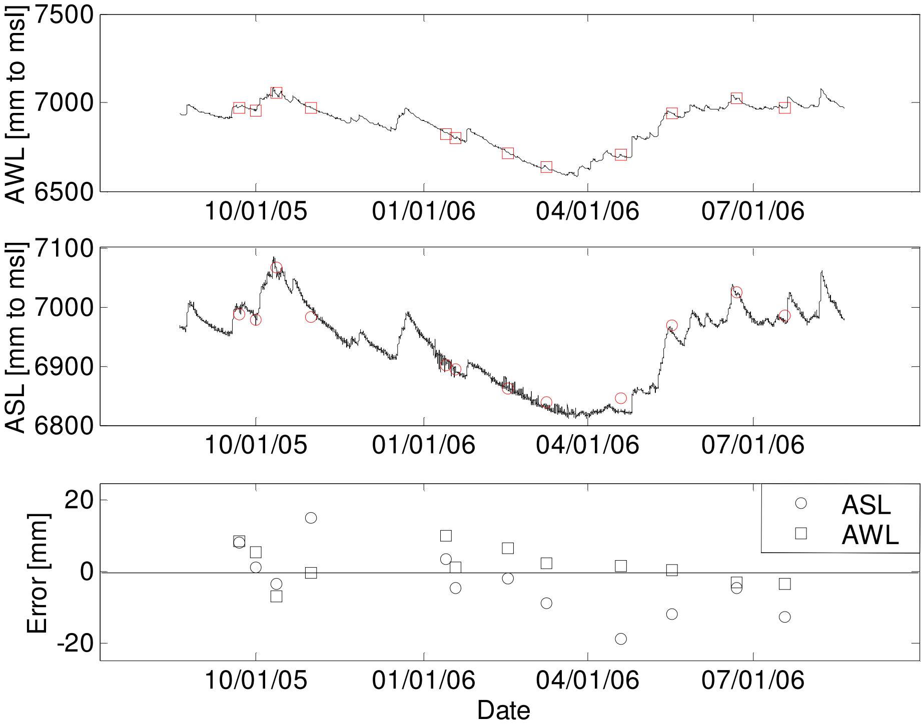

Figure A.2: Comparison between manual measurements (n=12) and automatic water level pressure transducers at site EW150. Upper graph shows AWL (solid line) and manual measurements (squares). Middle graph shows ASL (solid line) and manual measurements (circles). Lowest graph shows the deviation between automatic and manual measurements: Deviation for AWL measurements and ASL measurements is shown by squares and circles, respectively.

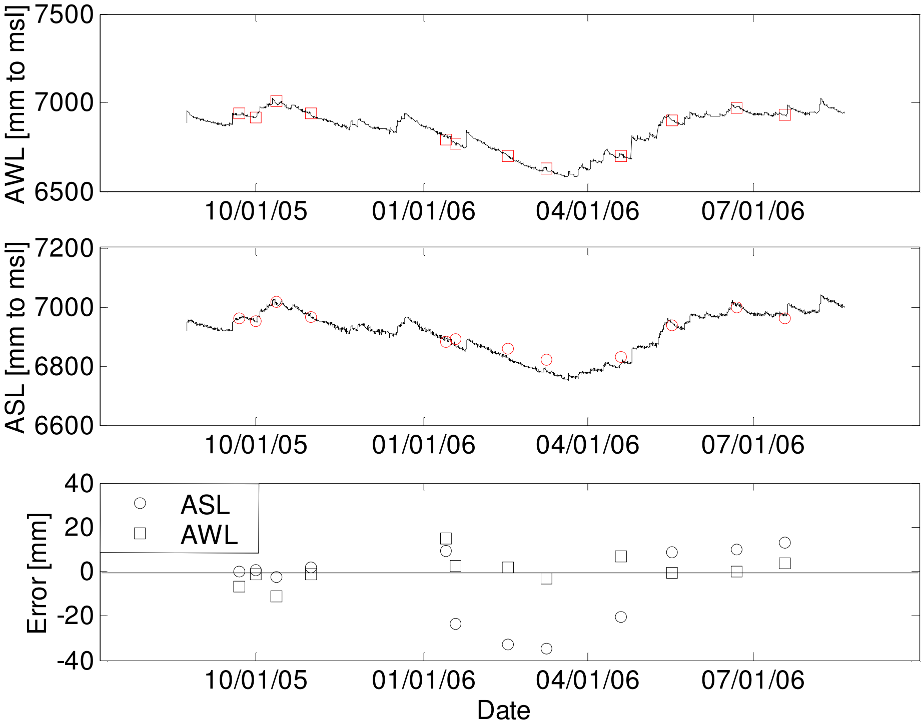

Figure A.3: Comparison between manual measurements (n=12) and automatic water level transducers (Dataflow capacitance probes 'Odyssey') at site NS100. Upper graph shows AWL (solid line) and manual measurements (squares). Middle graph shows ASL (solid line) and manual measurements (circles). Lowest graph shows the deviation between automatic and manual measurements: Deviation for AWL measurements and ASL measurements (AWL minus RWL) is shown by squares and circles, respectively.

Appendix B

Appendix B presents two continuous datasets of surface level and water level fluctuations additional to data discussed in Chapter three. Patterns are similar to patterns in Figure 3.3. However, the interpretation of the additional datasets is hampered by inaccurate measurements.

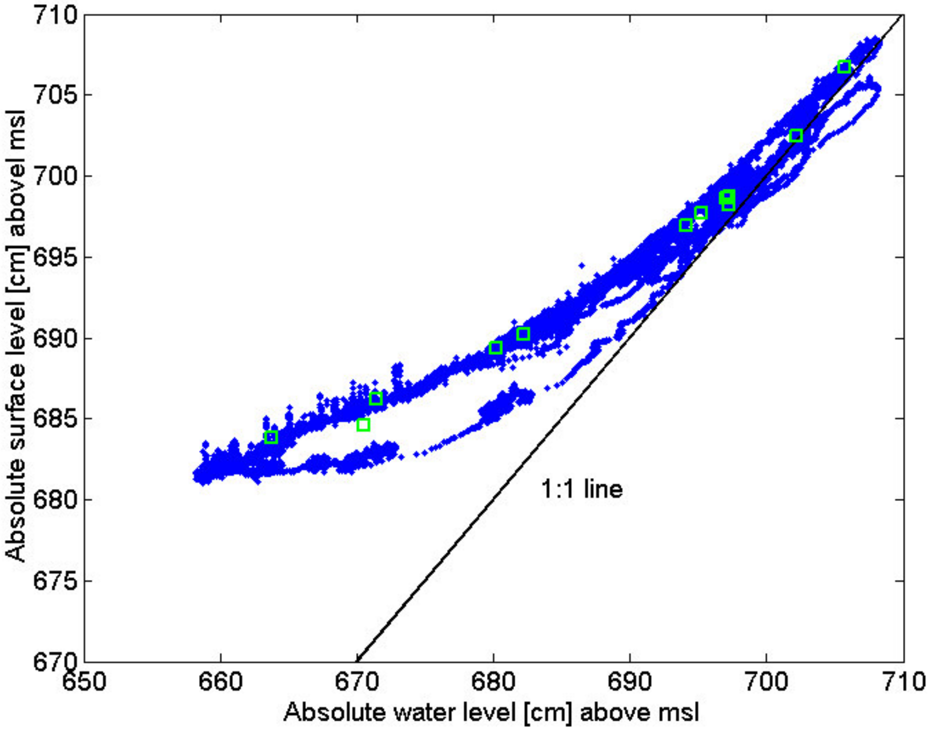

Figure B.1: Non-linear ASL-AWL relationship at site EW150 similar to Figure 3.3. Absolute surface level (ASL) against absolute water level (AWL) is plotted for a one-year period beginning 20 August 2005 comprising raw data as recorded by water level pressure transducers (ISD pressure transducer cf. A.2). Measuring interval was 15 min. The distance between data points and 1:1 line parallel to the y-axis indicates the thickness of the unsaturated zone. Note that ranges of axes differ.

The record of these transducers was notably noisy. However, patterns are similar to those in Figure 3.3. The loop that crosses the 1:1 line indicates flooding of site EW150 and was recorded at the very end of the monitoring period. Flooding was never observed during my frequent visits (n>60). Drift of the water level transducer as discussed in A.2 is suspected to cause this exceptional behaviour.

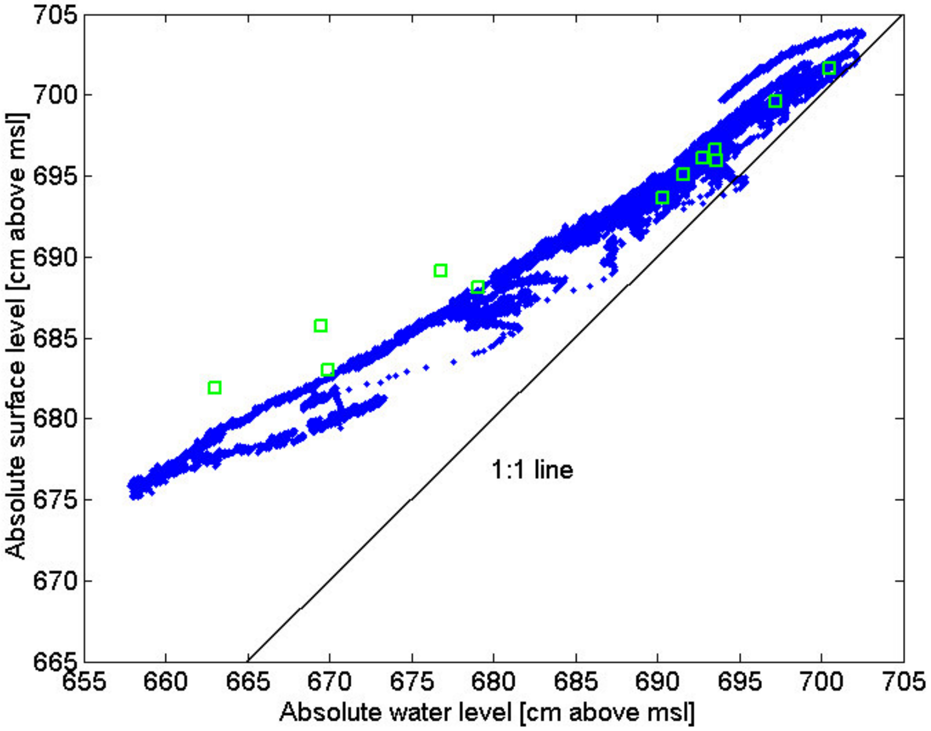

Figure B.2: ASL-AWL relationship at site NS100 similar to Figure 3.3. Absolute surface level (ASL) against absolute water level (AWL) is plotted for a one-year period beginning 20 August 2005 comprising raw data as recorded by water level capacitance transducers (Odyssey cf. A.3). Measuring interval was 15 min. The distance between data points and 1:1 line parallel to the y-axis indicates the thickness of the unsaturated zone. Note that ranges of axes differ.

Interpretation of the ASL-AWL relationship is hampered by the deviation between automatic and manual measurements of several centimetres particularly during the dry season (Figure A.3, E.1 and E.2). The automatic record suggests a 'more-or-less' linear ASL-AWL relationship. However, significantly higher surface levels during the dry season, as indicated by manual measurements, point towards non-linearity. This example stresses the fragility of surface elevation measurements to inaccurate monitoring (devices).

Appendix C

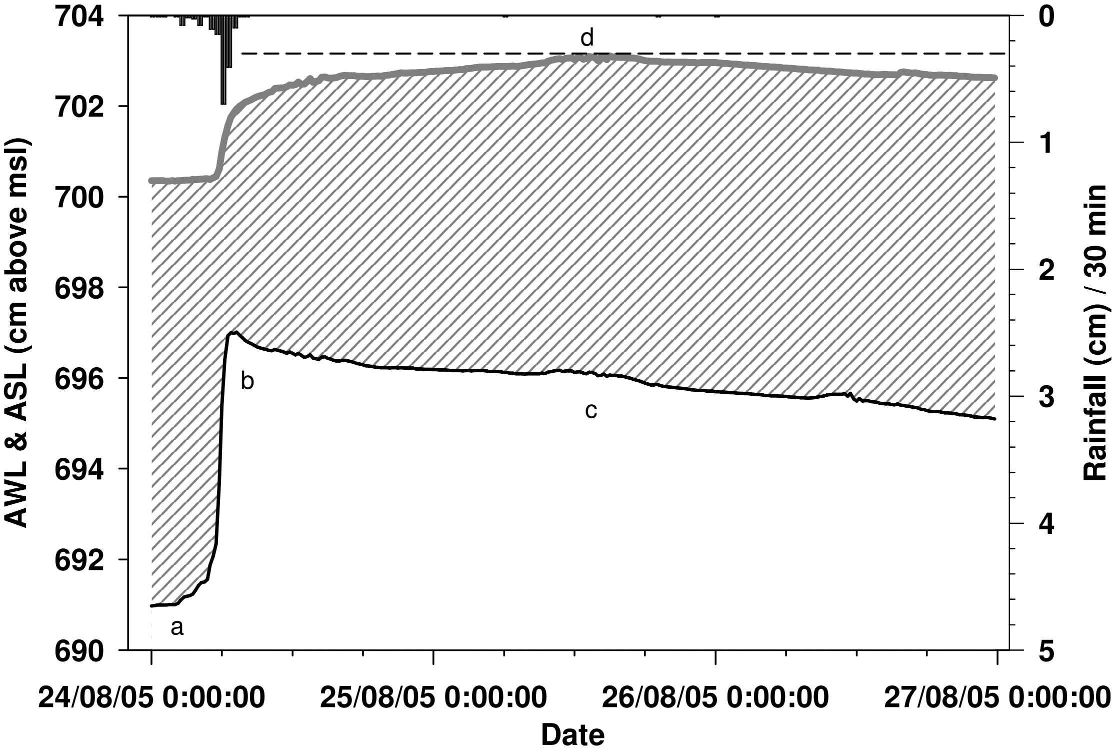

Figure C.1: Time series of rainfall (bars), absolute water level (AWL, lower line) and absolute surface level (ASL, upper line) at site NS400 that is presented in Figure 3.4, showing hysteresis of the ASL-AWL relationship for a single rain event (3.5 cm in 6 hours during wet season 2005, bars) based on 15-min data. The AWL raised by some 6 cm (a to b) causing an instant rise in ASL by some 1.8 cm (a to b). The water table stopped rising at b. The surface rose some millimetres despite an AWL draw down (b to c) reversing the ASL-AWL relationship. The climax of ASL (d) was reached some 38 h subsequent to the rain event. The shaded region represents the unsaturated zone and its thickness equals RWL (see also Figure 2.1). Dashed line indicates highest surface level.

Appendix D

Appendix D discusses 4 simulations of hysteretic behaviour of ASL fluctuations in peatlands (Figures D.1-D4). The key idea is that ASL will change subsequent to AWL fluctuations but this change is delayed in time. The simulations aim to test whether hysteretic PSO can result in a distinct drying and rewetting curve. Also tested is to what extent hysteresis can cause non-linearity of the ASL-AWL relationship. Therefore the relationship between ASL and AWL is *a priori* linear (OSC=0.6) but may become non-linear as a result of hysteresis.

Firstly, a very simple model of AWL fluctuations and ASL changes is assumed: Simulated was an absolute water level draw down at a constant rate of – 1 cm/day lasting 50 days followed by a rise at the same rate (1 cm/day) for 50 days. Resolution of this simulation is 1 hour. A higher resolution does not affect the ASL-AWL relationship. Hysteresis (ie. delay in ASL changes) is assumed to be constant but threefold: ASL changes by 50% instantly following AWL fluctuations, then 35% in the next 12 hours and the remaining 15% is realised in the following 24 hours. This delay-pattern is a rough estimation of ASL dynamics in Figure 3.3 and C.1

Key results of this simulation are the distinct character of a drying curve and a rewetting curve (Figure D.1). However, the drying and rewetting curve are spaced only 2 mm apart, which highlights the limited extent of hysteresis given these assumptions. Clearly, hysteresis is a function of time and faster AWL changes may result in a more pronounced hysteretic behaviour.
To explore the effects of rapid AWL changes the same hysteresis pattern (constant but threefold) is applied to the AWL data set as recorded at site NS400 (Figures A.1 and 3.2). A sequence of fast rewetting and slow drying cycles results in loops along the drying curve (Figure D.2) . Surprisingly the upper part of Figure D.2 is very similar to part ‘a’ in Figure 3.3. In contrast, the simulation fails to imitate the substantial delay of ASL changes after the dry season. A constant delay of ASL changes does not affect the linearity of the drying curve. So a small and constant hysteresis may explain the seasonal pattern of drying and rewetting but cannot simulate the extent of hysteresis.

Hysteresis is assumed to be dynamic in the second pair of simulations (Figures D.3 and D.4): the lower the surface level the stronger the hysteresis (ie. the more delayed ASL changes are). In Chapter 3 it was argued that hysteresis was more pronounced when the surface level was low and ASL changes may have occurred predominantly due to peat volume changes.

The delay pattern is assumed to be : 50 % of the ASL change occurred in the first x hours. 25% occurred in the next 2x x hours followed by 12.5% in the next 4x x hours and so on. In this simulation x was a polynomial function of the 4th order of ASL: x=1 hour at ASL 710 m above msl and x=200 hours for ASL 685 cm above msl.

If the same dynamic delay pattern is applied to a constant AWL draw down and subsequent rise (1 cm/day for 50 days), drying and rewetting curves reveal a clear seasonal pattern (Figure D.3). Drying and rewetting curves space most apart for low ASL and less for high ASL, which resembles the seasonal pattern in hysteresis as recorded at site NS400 (Figure 3.3). Although ASL changes are a linear function of AWL fluctuations (assumption in the simulation, slope 0.6 cm/cm) the dynamics of delay patterns force the ASL-AWL relationship to be convex ie. non-linear as indicated by the dashed line in Figure D.3. However, a flatter slope at the lower part of drying curve is much less pronounced than data suggest at site NS400 (Figure 3.3).

A simulation applying a dynamic delay-pattern on the AWL data set as recorded at site NS400 results in ASL dynamics (Figure D.4) that are surprisingly similar to the measured ASL (Figure 3.3). Loops along the drying curve and the seasonal differences between drying and rewetting curve are sufficiently redrawn by the simulation. However, the drying curve in Figure D.4 is linear (parallel to dashed line). Conclusively, a dynamic hysteresis explains well the temporal variability of the ASL-AWL relationship (eg. loops and drying and rewetting curve). I hypothesise that the seasonal pattern (drying curve vs. rewetting curve) is an artefact resulting from hysteresis of ASL changes. Furthermore, hysteresis may even add some non-linearity to the system. However, this contribution is minor.

More sophisticated models need to incorporate a non-linear ASL-AWL relationship.

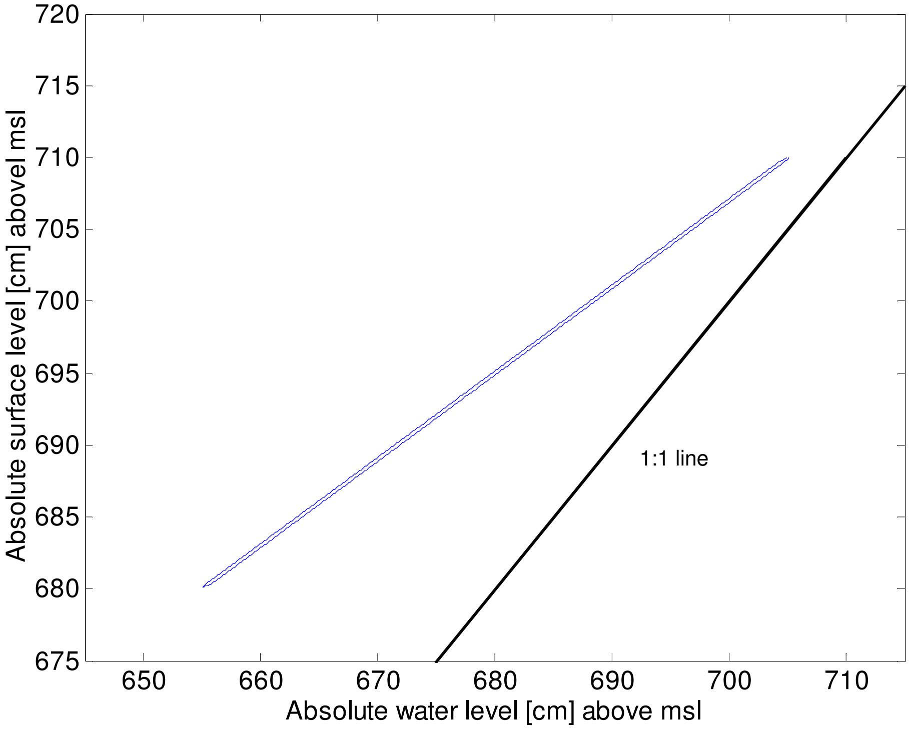

Figure D.1: ASL-AWL relationship for a constant AWL draw down and rise and a constant hysteresis. The graph consists of a drying curve and a rewetting curve that space only 0.2 cm apart (in the scale x-axis).

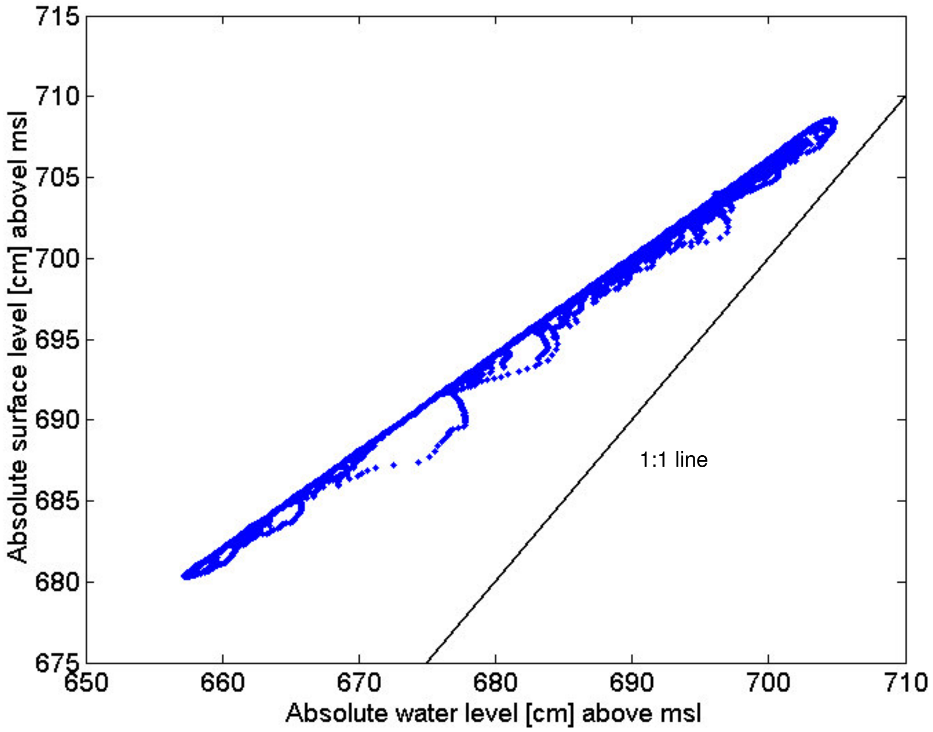

Figure D.2: Simulation of ASL fluctuations based on AWL fluctuations as monitored at site NS400 (cf. Figure 3.2 and 3.3). The setting of parameters is similar to D.1 (constant hysteresis).

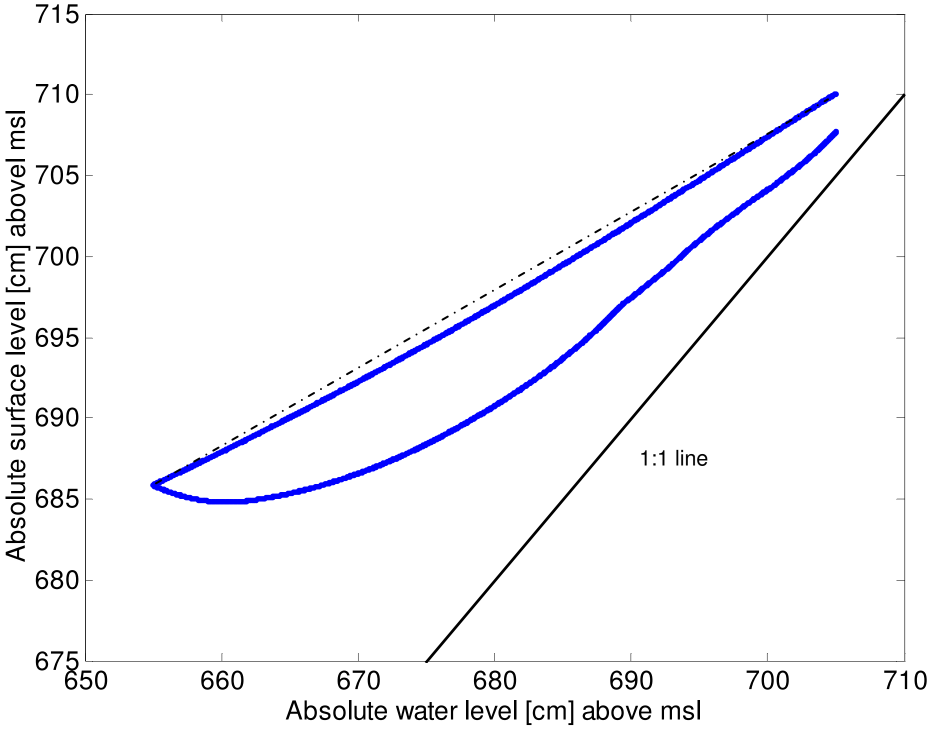

Figure D.3: ASL-AWL relationship for a constant AWL draw down and rise but a dynamic hysteresis. The delay increases with decreasing ASL. Dashed straight line highlights the slight non-linearity of the drying curve.

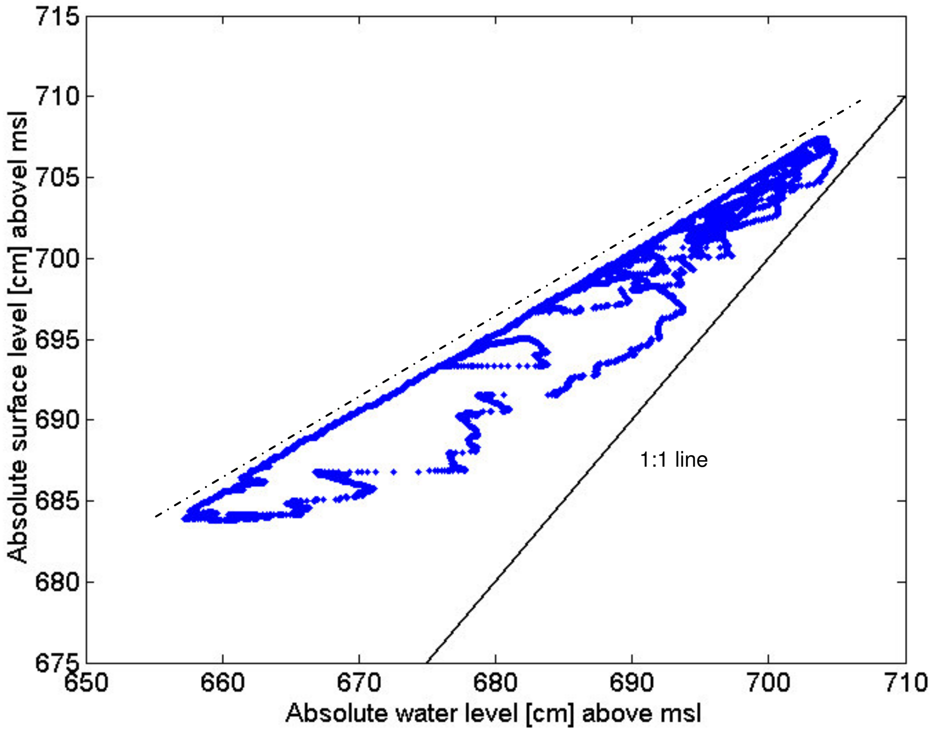

Figure D.4: Simulation of ASL fluctuations based on AWL fluctuations as monitored at site NS400 (cf. Figure 3.2 and 3.3). The setting of parameters is similar to D.3 (dynamic hysteresis). Dashed straight line highlights the linearity of the drying curve.

Appendix E

In Appendix A the precision of 3 different types of water level transducers was discussed. In the following figures it is shown that Odyssey capacitance sensors are inaccurate especially during drying cycles. Capacitance probes generally develop a film on their measuring device (capacitor) that mimic higher water levels. Films are 'wiped' out by rising water levels or by manual cleaning.

Therefore, data collected by these probes is not discussed in the main text.

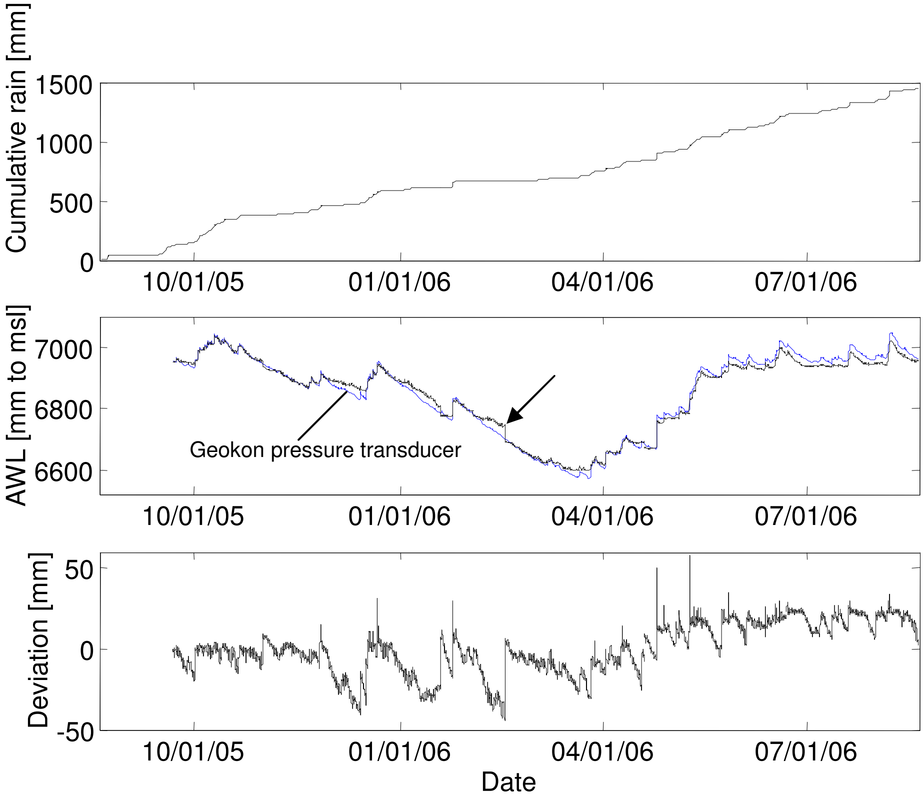

Figure E.1: Deviation between two automatic water level transducers measuring the absolute water level at site NS400 during a sequence of drying and rewetting cycles (rainfall as discussed in Chapter 3). Lower line in centre graph shows the water level as recorded by a pressure transducer (Geokon 4580-2v-2.5) that may serve as the reference here. Upper line shows the Odyssey capacitance probe data. One cleaning event is indicated by arrow (sharp return to zero of deviation curve).

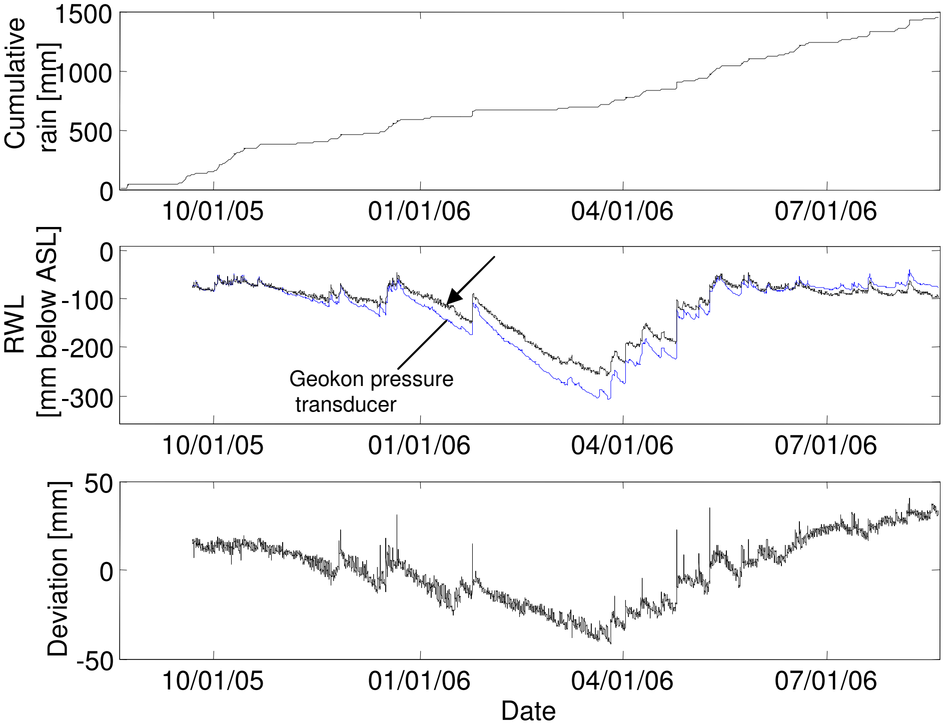

Figure E.2: Deviation between two automatic water level transducer measuring the relative water level (=water table below the surface[0 cm]) at site NS400 during a sequence of drying and rewetting cycles (rainfall as discussed in Chapter 3). Upper dashed line in centre graph shows the Odyssey capacitance probe and the lower line shows the water level as recorded by a pressure transducer (Geokon 4580-2v-2.5) that may serve as the reference here. One cleaning event is indicated by arrow that did not affect deviation between probes.

Appendix F

Table F.1. Ranges of water and surface levels as recorded across transect NS (north to south) and transect EW (east to west) in Opuatia wetland. Sites EW300 and NS350 were the same since transects intersected at this location.

Site	PSO [cm]	AWL fluctuation [cm]	OSC	RWL fluctuation [cm]	mean AWL [cm] above msl	mean ASL [cm] above msl	mean RWL [cm] above ASL
NS0	3.2	39.7	0.08	36.5	681.9	664.5	17.4
NS50	10.1	36.2	0.28	26.1	683.7	692.3	-8.6
NS100	19.7	37.5	0.53	17.8	685.0	692.2	-7.2
NS150	19	37.4	0.51	18.4	685.4	692.2	-6.8
NS200	14.5	37.3	0.39	22.8	685.5	696.5	-11.0
NS250	28	37.6	0.74	9.6	685.8	693.7	-7.9
NS300	14.5	39	0.37	24.5	686.1	688.4	-2.2
NS350	13.7	39.7	0.35	26.0	687.0	685.5	1.5
NS400	19.4	39.2	0.49	20.6	686.6	699.0	-12.4
NS450	14.8	41	0.36	27.1	686.6	691.7	-5.1
NS500	13.8	42.1	0.33	28.6	685.7	692.3	-6.6
NS550	12.5	42.1	0.30	29.6	685.2	694.6	-9.4
NS600	19.8	42.5	0.47	22.7	684.6	694.2	-9.6
NS650	12.5	40.7	0.31	28.2	683.4	682.2	1.1
EW0	3.2	45	0.07	42.0	688.7	672.5	16.2
EW50	24.1	43.3	0.56	19.2	688.9	703.6	-14.7
EW100	21.8	43.5	0.50	21.7	688.6	699.6	-11.0
EW150	22.9	41.9	0.55	19.7	688.2	694.4	-6.2
EW200	13.1	41.1	0.32	28.0	687.8	672.9	14.9
EW250	13.5	40.3	0.33	26.8	687.5	699.0	-11.5
EW300	13.7	39.7	0.35	26.0	687.0	685.5	1.5
EW350	10.2	38	0.27	28.4	686.7	698.9	-12.2
EW400	12.8	36.6	0.35	23.8	680.6	693.0	-12.4
EW450	5.4	32.6	0.17	29.0	656.5	663.7	-7.3
Mean	14.84	39.75	0.37	25.1	684.7	689.3	-4.6
SD	6.34	2.87	0.16	6.6	6.5	11.0	9.2

Table F.2: Peatland characteristics such as vegetation cover, peat thickness and bulk density as recorded across transect NS (north to south) and transect EW (east to west) in Opuatia wetland. The vegetation type was derived by agglomerative hierarchical clustering. Sites EW300 and NS350 were the same since transects intersected at this location.

Site	Trees %	Shrubs %	Restiads %	Sedges %	Herbs %	Peat thickness [m]	Bulk density [gcm^{-3}]	Vegetation type
NS0	10	30	0	30	20	1.00	0.12	3
NS50	0	12	65	5	25	3.00	0.09	1
NS100	0	15	65	5	35	5.00	0.05	1
NS150	0	0	65	10	35	7.00	0.08	1
NS200	0	0	70	5	25	8.20	0.08	1
NS250	0	0.5	70	5	35	10.00	0.10	1
NS300	0	12	50	10	30	8.00	0.09	1
NS350	0	3	40	20	35	5.50	0.09	2
NS400	0	8	65	5	40	6.00	0.08	1
NS450	0	12	50	20	30	8.00	0.09	2
NS500	0	6	30	30	30	9.00	0.10	2
NS550	0	3	40	20	25	12.00	0.10	2
NS600	0	20	65	20	30	11.00	0.06	2
NS650	0	8	20	30	30	12.00	0.10	2
EW0	20	20	0	30	30	2.50	0.18	3
EW50	0	1	80	11	30	6.50	0.09	1
EW100	0	4	70	15	40	8.30	0.09	1
EW150	0	0	75	15	25	10.00	0.06	1
EW200	0	25	20	20	30	8.80	0.07	2
EW250	0	1	40	25	30	7.00	0.08	2
EW300	0	3	40	20	35	5.50	0.09	2
EW350	0	0	65	20	35	4.20	0.08	1
EW400	0	5	60	15	35	2.80	0.08	1
EW450	40	35	0	10	60	0.80	0.11	3
Mean	3.04	9.59	48.04	16.35	32.17	6.81	0.09	2.52
SD	9.26	10.27	25.30	8.79	7.81	3.30	0.03	0.51

Appendix G

Table G.1: Extended review table (Table 2.1). Many sites and study periods were summarised. Column 2 (period and frequency) comprises of study period, the season in which study commenced and the measurement frequency. Abbreviations are as the following:

•1. Duration in years;
•2. Season: sp=spring, s=summer, a=autumn, w=winter;
•3. Frequency: con=continuous, d=daily, w=weekly, f=fortnightly, m=monthly, qua=3-monthly, hy=6-monthly, y=yearly.

Peat type contains a very rough description of the dominating plant remains of the uppermost peat (0.5-1m). Dry bulk density data were usually measured from surface samples of peat (typically 3-10 cm deep). Some studies stated values that were conceptually comparable to the oscillation coefficient used here.

Reference	Period	Peatland type	Peat type	Peat thickness [m]	Bulk density [g cm-3]	Absolute water level [cm]	Relative water level [cm]	Surface level changes [cm]	Oscilla-tion coeffcient	Term	Peatland name
Barber *et al.* (2004)	6	disturbed peatland	sedge wood	6.0		100		6		soil elevation changes	Tadham Moor
Gilman (1994)	1, sp, f	disturbed peatland	sedge wood	3.7-5.4		29		3.4		ground movement	Crymlyn 1985
Gilman (1994)	1, sp, f	disturbed peatland	sedge wood	3.7-5.4		58		5.6		ground movement	Crymlyn 1986
Gilman (1994)	1, sp, f	disturbed peatland	sedge wood	3.7-5.4		50		7.1		ground movement	Crymlyn 1987
Gilman (1994)	1, sp, f	disturbed peatland	sedge wood	3.7-5.4		43		5.3		ground movement	Crymlyn 1988
Gilman (1994)	0.75, sp, f	disturbed peatland	sedge wood	3.7-5.4		70		9.4		ground movement	Crymlyn 1989
Gilman (1994)	2, sp, f	disturbed peatland	sedge wood	4.5-5		90		7.0-13.0	0.2 0.15 0.12	ground movement	West Sedgemoor 1988-90
Kennedy and Price (2005)	0.3, s, f	disturbed peatland	Sph	2.9			26	2.8		peat volume changes	Lac Saint-Jean cutover peatland - unharvested site
Kennedy and Price (2005)	0.3, s, f	disturbed peatland	Sph	1.9			35	5.5		peat volume changes	Lac Saint-Jean cutover peatland - '2-year site'
Kennedy and Price (2005)	0.3, s, f	disturbed peatland	Sph	1.7	0.1		46	2.5		peat volume changes	Lac Saint-Jean cutover peatland - '7-year site'
Kennedy and Price (2005)	0.1, s, w	disturbed peatland	Sph	1.7	0.1		18	3	0.17	peat volume changes	Lac Saint-Jean cutover peatland - '7-year site'
Kennedy and Price (2005)	0.1, s, w	disturbed peatland	Sph	1.7	0.1		18	0.7	0.04	peat volume changes	Lac Saint-Jean cutover peatland - '7-year site'
Kennedy and Price (2005)	0.1, s, w	disturbed peatland	Sph	1.7	0.1		38	5.3	0.14	peat volume changes	Lac Saint-Jean cutover peatland - '7-year site'

Reference	Period	Peatland type	Peat type	Peat thickness [m]	Bulk density [g cm-3]	Absolute water level [cm]	Relative water level [cm]	Surface level changes [cm]	Oscilla-tion coeffcient	Term	Peatland name
Kennedy and Price (2005)	0.1, s, w	disturbed peatland	Sph	1.7	0.1		36	2.6	0.07	peat volume changes	Lac Saint-Jean cutover peatland - '7-year site'
Kennedy and Price (2005)	0.04, s, w	disturbed peatland	Sph	1.7	0.1		20	2.5	0.12	peat volume changes	Lac Saint-Jean cutover peatland - '7-year site'
Kennedy and Price (2005)	0.04, s, w	disturbed peatland	Sph	1.7	0.1		28	1.3	0.05	peat volume changes	Lac Saint-Jean cutover peatland - '7-year site'
Kennedy and Price (2005)	0.02, s, w	disturbed peatland	Sph	1.7	0.1		18	1.4	0.08	peat volume changes	Lac Saint-Jean cutover peatland - '7-year site'
Kennedy and Price (2005)	0.04, s,w	disturbed peatland	Sph	1.7	0.1		13	1	0.08	peat volume changes	Lac Saint-Jean cutover peatland - '7-year site'
Price and Schlotzhauer (1999)	0.4, s, d	disturbed peatland	Sph	1.7	0.083-0.105	79		7	0.09	peat volume changes	Lac Saint-Jean cutover peatland - '92-site'
Price and Schlotzhauer (1999)	0.4, s, d	disturbed peatland	Sph	1.7	0.083-0.105	80		7	0.09	peat volume changes	Lac Saint-Jean cutover peatland - '92-site'
Price and Schlotzhauer (1999)	0.4, s, d	disturbed peatland	Sph	1.7	0.083-0.105	60		9	0.15	peat volume changes	Lac Saint-Jean cutover peatland - '92-site'
Price and Schlotzhauer (1999)	0.4, s, d	disturbed peatland	Sph	1.7	0.083-0.105	55		7.5	0.14	peat volume changes	Lac Saint-Jean cutover peatland - '92-site'
Price (2003)	0.5, s, f	disturbed peatland	Sph	2.9			40	4.5		peat volume changes	Lac Saint-Jean cutover peatland - unharvested site
Price (2003)	0.5, s, f	disturbed peatland	Sph	1.9			50	7.5		peat volume changes	Lac Saint-Jean cutover peatland - '2-year site'
Price (2003)	0.5, s, f	disturbed peatland	Sph	1.7	0.1		75	4		peat volume changes	Lac Saint-Jean cutover peatland - '7-year site'
Schothorst (1977)	6, sp; qua	disturbed peatland	wood sedge	7.0	0.55	50		7		surface elevation fluctuation	Zegvelderbroek

Reference	Period	Peatland type	Peat type	Peat thickness [m]	Bulk density [g cm-3]	Absolute water level [cm]	Relative water level [cm]	Surface level changes [cm]	Oscilla-tion coeffcient	Term	Peatland name
Schothorst (1977)	6, sp; qua	disturbed peatland	wood sedge	7.0	0.55	50		7		surface elevation fluctuation	Zegvelderbroek
ter Hoeve (1969)	1.1, w, m	disturbed peatland	Sph	3.9		28		3.3		Mooratmung	Engbertsdijksvenen
ter Hoeve (1969)	1.1, w, m	disturbed peatland	Sph	3.9		23		3.2		Mooratmung	Engbertsdijksvenen
ter Hoeve (1969)	11.1, w, m	disturbed peatland	Sph	3.5		15		2		Mooratmung	Engbertsdijksvenen
Van Seters and Price (2001)	0.17, s, f	disturbed peatland	Sph	4.0	0.07-0.13		26.3	1	0.037	surface elevation changes	Cacouna bog
Van Seters and Price (2001)	0.25, s, f	disturbed peatland	Sph	4.0	0.07-0.13		33.4	1.6	0.046	surface elevation changes	Cacouna bog
Van Seters and Price (2001)	0.25, s, f	disturbed peatland	Sph	4.6			19.8	1.1	0.054	surface elevation changes	St Arsène peatland
Whittington and Price (in press)	0.25, s, w	disturbed peatland	sdg	0.8	0.1	11		1		peat volume changes	poor fen near St. Charles-de-Bellechasse
Whittington and Price (in press)	0.25, s, w	disturbed peatland	sdg	0.8	0.1	16		1		peat volume changes	poor fen near St. Charles-de-Bellechasse
Whittington and Price (in press)	0.25, s, w	disturbed peatland	sdg	1.0	0.08					peat volume changes	poor fen near St. Charles-de-Bellechasse
Whittington and Price (in press)	0.25, s, w	disturbed peatland	sdg	1.0	0.08					peat volume changes	poor fen near St. Charles-de-Bellechasse
Whittington and Price (in press)	0.25, s, w	disturbed peatland	sdg	1.0	0.08					peat volume changes	poor fen near St. Charles-de-Bellechasse
Baden and Eggelsmann (1964)		disturbed peatland	Sph					1.5-3		Mooratmung	various peatlands in NW Germany

Reference	Period	Peatland type	Peat type	Peat thickness [m]	Bulk density [g cm-3]	Absolute water level [cm]	Relative water level [cm]	Surface level changes [cm]	Oscilla-tion coeffcient	Term	Peatland name
Eggelsmann (1964)		disturbed peatland	Sph					2.3-6		Mooratmung	various peatlands in NW Germany
Eggelsmann (1981)		disturbed peatland					18-72	0.7-4.2		oscillation	varies peatlands, mainly disturbed
Glaser *et al.* (2004)	0.33, s, con	fen	Sedge	3.0			2.5	6		surface deformation	Red lake peatland raised fen
Glaser *et al.* (2004)	0.33, s, con	fen	Sedge	3.0			2.5	20		surface deformation	Red lake peatland raised fen
Kellner *et al.* (2005)	0.33, s, w	fen	Sedge	1.2	0.05		22	10		peat volume changes	poor fen near St. Charles-de-Bellechasse
Kellner *et al.* (2005)	0.33, s, w	fen	Sedge	1.2	0.05		14	9		peat volume changes	poor fen near St. Charles-de-Bellechasse
Nuttle *et al.* (1990)	0.25,s,d	fen	wood silicat	1.0		27		0.8		surface displacement	Belle Isle marsh
Nuttle *et al.* (1990)	0.25,s,d	fen	wood silicat	1.0		14		0.4		surface displacement	Sippewisset marsh
Nuttle *et al.* (1990)	0.25,s,d	fen	wood silicat	4.5		12		2.3		surface displacement	Sippewisset marsh
Price (1994)	0.25, s, con	fen	Typha peat	0.6		40		0.8		surface adjustment	Bayfield Bay Typha marsh (lake Ontario)
Schipper and Loss (2003)	0.33, s, w	fen	Sedge	4.2			7.75	2.5		mire oscillation	a pristine valley mire of the Ob River
Swarzenski *et al.* (1991)	0.17,a, w	fen	root peat	0.5	0.16	45	42	3		surface movement	Bajou rigolette

Reference	Period	Peatland type	Peat type	Peat thickness [m]	Bulk density [g cm-3]	Absolute water level [cm]	Relative water level [cm]	Surface level changes [cm]	Oscillation coeffcient	Term	Peatland name
Tanneberger and Hahne (2003) & Schipper and Loss (2003)	0.33, s, w	fen	Sedge	3.5			11.5	0.5		mire oscillation	a pristine valley mire of the Ob River
Tanneberger and Hahne (2003) Schipper and Loss (2003)	0.33, s, w	fen	Sedge	3.7			13.5	1.5		mire oscillation	a pristine valley mire of the Ob River
Tanneberger and Hahne (2003) Schipper and Loss (2003)	0.33, s, w	fen	sedge brownmoos	5.0			9.83	2		mire oscillation	a pristine valley mire of the Ob River
Tanneberger and Hahne (2003) Schipper and Loss (2003)	0.33, s, w	fen	sedge brownmoos	5.2			7.75	4.5		mire oscillation	a pristine valley mire of the Ob River
Touber (1973)	0.25,s,m	fen	sedge brownmoos	0.6		10		1		Kragge movement	Grafkampen
Touber (1973)	0.25,s,m	fen	sedge brownmoos	0.6		9		1		Kragge movement	Kahlenberg
Touber (1973)	0.25,s,m	fen	sedge brownmoos	0.6		8		0.5		Kragge movement	Stobbenribben
Almendinger *et al.* (1986)	1, s, hy	fen	Sedge	2.6				6		topographic fluctuations	Lost River peatland spring fen

Reference	Period	Peatland type	Peat type	Peat thickness [m]	Bulk density [g cm-3]	Absolute water level [cm]	Relative water level [cm]	Surface level changes [cm]	Oscilla-tion coeffcient	Term	Peatland name
Almendinger *et al.* (1986)	1, s, hy	fen	Sedge	2.2				1.5		topographic fluctuations	Lost River peatland fen
Holm *et al.* (2000)		fen						3.0-30.0			Oligohaline marshes in Louisiana
Baumann (2006)	0.25, s, w	bog	Sph	4.5			29	2.9		mire oscillation	Andorra valley bog
Baumann (2006)	0.25, s, w	bog	Sph	7.0			14.5	3.6		mire oscillation	Andorra valley bog
Baumann (2006)	0.25, s, w	bog	Sph	7.0			20.5	3.1		mire oscillation	Andorra valley bog
Baumann (2006)	0.25, s, w	bog	Sph	7.0			22	3.1		mire oscillation	Andorra valley bog
Baumann (2006)	0.25, s, w	bog	Sph	5.4			30	3		mire oscillation	Andorra valley bog
Baumann (2006)	0.25, s, w	bog	Sph	7.0			20.5	4		mire oscillation	Andorra valley bog
Baumann (2006)	0.25, s, w	bog	Sph	5.0			20.5	1.5		mire oscillation	Andorra valley bog
Fox (1984)	2.25, sp, con	bog	Sph	7.0		13		6.4		mire breathing	Cors Fochno Bog
Glaser *et al.* (2004)	0.33, s, con	bog	Sph	4.3			11	4		surface deformation	Red lake peatland raised bog
Glaser *et al.* (2004)	0.33, s, con	bog	Sph	4.3			11	20		surface deformation	Red lake peatland raised bog
Kellner and Halldin (2002)	1.5, s, con	bog	Sph	3.5		30		4		mire breathing	Stormossen
Tsuboya *et al.* (2001)	0.25,s,con	bog	sph	6.0		23		7		surface movement	Sarobetsu Mire
Tsuboya *et al.* (2001)	0.25,s,con	bog	sph	6.0		16		5		surface movement	Sarobetsu Mire

Reference	Period	Peatland type	Peat type	Peat thickness [m]	Bulk density [g cm-3]	Absolute water level [cm]	Relative water level [cm]	Surface level changes [cm]	Oscilla-tion coeffcient	Term	Peatland name
van der Schaaf (1999)	1.1, sp, f	bog	Sph	12.5	0.042		15	6.7		bog breathing, seasonal oscillation of the surface level	Raheenmore Bog
van der Schaaf (1999)	1.1, sp, f	bog	Sph	2.9	0.084		40	5.6		bog breathing, seasonal oscillation of the surface level	Raheenmore Bog
van der Schaaf (1999)	2.2, sp, f	bog	Sph	8.0	0.056		12	10.9		bog breathing, seasonal oscillation of the surface level	Clara West Bog
van der Schaaf (1999)	2.2, sp, f	bog	Sph	4.5	0.1176		36	3.2		bog breathing, seasonal oscillation of the surface level	Clara West Bog
Almendinger *et al.* (1986)	1, s, hy	bog	Sph	4.0				11		topographic fluctuations	Lost River peatland raised bog
Baird *et al.* (2004)		floating peatland	root peat (Cladium)					5.0-10.0		vertical (mat) movement	several peatlands in Broadland lake area
Buell and Buell (1941)	5, a, hy	floating peatland	Sedge-wood - peat	3.0				11.9		surface level fluctuation	CedarCreek Bog
Buell and Buell (1941)	5, a, hy	floating peatland	Sedge-wood - peat	3.3				19.2		surface level fluctuation	CedarCreek Bog
Buell and Buell (1941)	5, a, hy	floating peatland	Sedge-wood - peat	3.0				18.0		surface level fluctuation	CedarCreek Bog

Reference	Period	Peatland type	Peat type	Peat thickness [m]	Bulk density [g cm-3]	Absolute water level [cm]	Relative water level [cm]	Surface level changes [cm]	Oscilla-tion coeffcient	Term	Peatland name
Buell and Buell (1941)	**5, a, hy**	**floating peatland**	**Sedge-wood - peat**	**2.6**				**21.0**		**surface level fluctuation**	**CedarCreek Bog**
Buell and Buell (1941)	**5, a, hy**	**floating peatland**	**Sedge-wood - peat**	**2.6**				**26.2**		**surface level fluctuation**	**CedarCreek Bog**
Buell and Buell (1941)	**5, a, hy**	**floating peatland**	**Sedge-wood - peat**	**1.7**				**45.1**		**surface level fluctuation**	**CedarCreek Bog**
FechnerLevy and Hemond (1996)	**0.5, s, con**	**floating peatland**	**Sph**	**2.0**		**21**	**3**	**18**	**0.9**	**absolute floating mat level changes**	**Thoreau's bog**
Gates (1940)	**17, s, y**	**floating peatland**	**brownmoss**	**3.9**				**67.1**		**level fluctuation**	**Mud Lake Bog**
Green and Pearson (1968)	**2, w, w**	**floating peatland**	**Sph**	**4.0**		**17**	**10**	**12**		**peat raft movement**	**Wybunbury Moss**
Hogg and Wein (1988)		**floating peatland**	**root peat (Typha)**	**0.5**			**3**			**mat buoyancy**	**Hog Lake**
Koerselman (1989)	**1, sp, w**	**floating peatland**	**Sedge**	**0.6**		**20**		**3.5**		**root mat oscillation**	**Westbroek polder**
Price (1994)	**0.25, s, con**	**floating peatland**	**Typha peat**	**5.0**		**40**		**12**		**surface adjustment**	**Bayfield Bay Typha marsh (lake Ontario)**
Price (1994)	**0.25, s, con**	**floating peatland**	**Typha peat**	**2.6**		**34**		**10**		**surface adjustment**	**Bayfield Bay Typha marsh (lake Ontario)**
Roulet *et al.* (1991)	**0.25,s,con**	**floating peatland**	**sedge brownmoos**	**1.5**		**9.5**	**9**	**4.4**		**surface fluctuation**	**fen near Schefferville**

Reference	Period	Peatland type	Peat type	Peat thickness [m]	Bulk density [g cm-3]	Absolute water level [cm]	Relative water level [cm]	Surface level changes [cm]	Oscilla-tion coeffcient	Term	Peatland name
Roulet (1991)	0.17, s, w	floating peatland	sedge brownmoos	1.8		5.8	0	5.8		fluctuations of the surface level	Arés fen
Roulet (1991)	0.17, s, w	floating peatland	sedge brownmoos	1.8		10.6	0	10.6		fluctuations of the surface level	Arés fen
Roulet (1991)	0.17, s, w	floating peatland	sedge brownmoos	1.8		5	4	3.1		fluctuations of the surface level	Arés fen
Roulet (1991)	0.17, s, w	floating peatland	sedge brownmoos	0.5		6	1.7	4.9		fluctuations of the surface level	Arés fen
Swarzenski *et al.* (1991)	1, s, con	floating peatland	root peat	1.6	0.07	70	18	55		surface movement	Lake Boeuf
Swarzenski *et al.* (1991)	1, s, con	floating peatland	root peat	1.3	0.07	70	50	35		surface movement	Lake Salvador
Touber (1973)	0.25,s,m	floating peatland	sedge brownmoos	0.6		15		9		Kragge movement	Grafkampen
Touber (1973)	0.25,s,m	floating peatland	sedge brownmoos	0.6		3		2.5		Kragge movement	Grafkampen
Touber (1973)	0.25,s,m	floating peatland	sedge brownmoos	0.6		9		9		Kragge movement	Kahlenberg

Reference	Period	Peatland type	Peat type	Peat thickness [m]	Bulk density [g cm-3]	Absolute water level [cm]	Relative water level [cm]	Surface level changes [cm]	Oscilla-tion coefficient	Term	Peatland name
Touber (1973)	0.25,s,m	floating peatland	sedge brownmoos	0.6		23		7		Kragge movement	Stobbenribben
Touber (1973)	0.25,s,m	floating peatland	sedge brownmoos	0.6		14		3		Kragge movement	Stobbenribben
Touber (1973)	0.25,s,m	floating peatland	sedge brownmoos	0.6		14		5		Kragge movement	Stobbenribben
Touber (1973)	0.25,s,m	floating peatland	sedge brownmoos	0.6		19		12		Kragge movement	Stobbenribben
Touber (1973)	0.25,s,m	floating peatland	sedge brownmoos	0.6		8		7		Kragge movement	Stobbenribben
Whittington and Price (in press)	0.25, s, w	floating peatland	Sedge	1.2	0.05	7.5		6.5		peat volume changes	poor fen near St. Charles-de-Bellechasse
Roulet *et al.* (1992)		floating peatland							0.03-0.5; 1	peat surface rise/fall	floating fens near Schefferville
van Wirdum (1991)		floating peatland	sedge brownmoos					several cm		Kragge movement	floating fens in northern Netherlands
Ingram (1983)		all mires						several cm		mire breathing	all mires