



**WATER-BASED QUARRY
RESTORATION: OPPORTUNITIES
FOR SUSTAINABLE RURAL
REGENERATION AND NATURE
CONSERVATION
MA/6/2/013**

**DRAFT VERSION 1
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**FLOATING WETLANDS:
ASSESSMENT OF VIABILITY AS A
METHOD FOR THE RESTORATION
OF WET MINERAL WORKINGS
MA/6/2/013**

**DRAFT VERSION 1
March 2008**

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DISCLAIMER

This publication and references within it to any methodology, process, service, manufacturer or company do not constitute its endorsement or recommendation by the Minerals Industry Research Organisation or the Department for Environment, Food and Rural Affairs.

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1 INTRODUCTION

Sub-watertable mineral extraction has been undertaken for hundreds of years, resulting in the creation of large areas of wetland and numerous waterbodies. Many of these have significant ecological and public amenity benefit and are important resources at regional and national levels. Historically the majority of restoration was generally passive and unplanned. However, increasing public awareness, greater understanding of the water environment and progressive tightening of planning regulations and European Union (EU) directives have placed a greater emphasis on the optimisation of water-based restoration design. This is appropriate given the long-term effects of restoration compared with the relatively short operational life of a quarry and the proven potential for schemes to make a major beneficial contribution to the surrounding area.

Hafren Water in conjunction with quarry operators, nature conservation organisations and regulatory authorities has recently completed a research project funded by the Minerals Industry Research Organisation (MIRO) entitled 'Water-based quarry restoration: methodologies, technologies and approaches' (MA/5/2/2005) (www.quarry-restoration.com).

The project identified several innovative approaches to restoration which have been developed further under the research project title, Water-based Quarry Restoration - opportunities for sustainable rural regeneration and nature conservation (MA/6/2/013).

1.1 Report layout

For ease of reference the project has been sub-divided into two self-contained reports relating to the different research topics. This report relates to the assessment of floating wetlands as discussed below:

1.2 Project background

Historically, the Swale and Ure Washlands in North Yorkshire have been characterised by extensive areas of fen and mire rather than open water (Hammond, 2007a). An assessment of opportunities for wetland re-creation in the Swale and Ure Washlands in North Yorkshire has indicated that there are very few potential sites in the farmed countryside. This reflects inherent difficulties in restoring favourable hydrological conditions together with the excessive nutrient loads in agricultural soils and surface drainage waters. At the same time, aggregate extraction is creating extensive areas of deep open water but very little vegetated wetland. These waterbodies have biodiversity value (usually as eutrophic or mesotrophic lakes) and can be designed to maximise shorelines and incorporate shallow margins, reedbeds, bird nesting islands, etc (White & Gilbert, 2003). However, associated problems include bird strike hazards (due to large populations of flocking water birds close to airfields) and the need to reduce mineral extraction to provide residual materials for landforming to meet planning/landscape/conservation requirements, consequently leading to a greater requirement for land elsewhere.

A potential solution to these challenges, at least on a modest scale, could be to establish wetland vegetation over the surface of open waterbodies. This may seem a paradox but 'floating' or 'raft-forming' wetlands are widespread in nature (**Figures 1 and 2**) whilst fabricated vegetation rafts are being used in several countries for management of the water environment (eg wildlife/fishery habitat, erosion control, nutrient sequestration, pollution remediation).

If successful, this technique could make a substantial contribution to UK and local BAP targets, and re-create historically-characteristic fen and mire habitats which have almost disappeared from the Yorkshire lowlands. Also in some cases mineral is being sterilised to provide

restoration material for habitat creation. The possibility exists for floating wetlands to lead to an increase in mineral recovery and a reduction in the extent of open waterbodies.

2 PROJECT OBJECTIVES

The objective was a review of floating wetlands in a global context and to identify some of the principal features characterising these distinctive habitats. The current status of floating wetland restoration techniques was assessed and the ecological and hydrological issues related to raft viability was related to the practical engineering aspects of the restoration of open water in a quarry environment. The project ran over a 10-month period and was intended to provide an assessment of the feasibility of floating wetland quarry-restoration with the potential to extend the project in the future. Key elements of the project included an assessment of the hydro-ecological environment and the influence that this will have on the final restoration scheme. Part of the research was to initiate field trials at 2 case study sites in North Yorkshire. These trials were intended to obtain a practical insight into the deployment of the rafts using existing 'floating island' technology and inform the planning of further field trials based on additional methods derived during the process of this project. Less than a single growing season was available for the project and longer duration trials will be required to assess the development of the raft-forming vegetation. Suggestions are made as to possible applications to the quarry environment as a basis for further applied research.

3 APPROACH

As part of MIST Thematic Priority 2: *Site design, operation and closure*, a review of the methodology and approaches used for the research project was undertaken within published literature and through discussions with interested parties. The floating wetlands project involved a desk study plus limited field trials with a view to developing the scale of the project at a later date. The work involved input from experts in the fields of ecology, landscape, planning, hydrogeology, hydrology, sustainable energy, engineering and quarry operations. A steering group was set up composed of partner members who monitored progress and provided input to the investigation.

Priority was given to the dissemination of information through the website (www.quarry-restoration.com) and presentations to the Steering Group Committee. The project aimed to provide practical guidance to promote innovative approaches to future water-based restoration schemes.

The present study comprises a review of floating wetlands in a global context and attempts to distil some of the principal features characterising these distinctive habitats. A brief review of the use of fabricated floating rafts for habitat creation has also been included. Finally, some suggestions are made as to possible applications to the quarry environment as a basis for further applied research.

3.1 Data sources

Data was obtained from the operating company and regional data including river levels, rainfall and groundwater levels were obtained from the Environment Agency. Published data was obtained from the scientific literature and detailed internet searches. Site visits were made and discussions held with interested parties including quarry operators, restoration managers and reserve trusts. A site visit was made to the nurseries of AGA Ltd to obtain information on floating island technology in the UK. Telephone discussions were held with other floating island manufacturers and the Department of Agriculture at the University of Louisiana who have been researching the floating wetland restoration on a habitat scale.

3.2 Project partners

Considerable support was provided for this project from quarry operators (Tarmac and Lafarge), Natural England and North Yorkshire County Council.

The project was a collaborative venture between industry and public sector organisations including:

- Hafren Water – Dr P Ellis (Hydrogeologist), Mr C Leake (Director)
- Mr M Hammond (Wildlife Consultant)
- Tarmac Northern – Mr C Arditto (Geological Manager), Mr M Young (Estates Manager)
- Lafarge Aggregates – Mr D Park (Restoration Manger),
- Natural England – Mr T Kohler
- North Yorkshire County Council – Mr M Barnett (Principal Landscape Architect), Mr G Megson (Natural Environment Team Leader)

3.3 Website

The project website (www.quarry-restoration.com) has been operational since October 2005 and will be maintained for several years following completion of the project. Interested parties are encouraged to use, contribute and link to it.

3.4 Case study areas and field trials

Two sites were selected for initial field trials using available floating wetland technology.

3.4.1 Nosterfield Quarry

Nosterfield Quarry in Yorkshire contains several large open waterbodies and the operators Tarmac were keen to examine the options for 'breaking' these up to increase biodiversity and potentially influence bird strike issues. The quarry site comprises a partly restored area and active area of sand and gravel extraction operated by Tarmac. Adjacent to the site is Nosterfield Nature Reserve comprising restored former sand and gravel workings managed primarily for wetland birds (see www.luct.org.uk). A partially completed restoration of the working quarry site includes areas of open water, reedbeds, limestone grassland and an experiment currently underway to create a fen using peat stripped from a future extraction area.

Further details of the Nosterfield site are available within the earlier research report (MA/5/2/005) available for download from the project website.

3.4.2 Hatfield Moor Nature Reserve

The former sand and gravel pits at Hatfield Moor is operated by Natural England as part of the Humberhead Peatlands National Nature Reserve. The site has provided a useful trial site for some of the work, and the information generated may be of direct relevance to restoration of the site. Resources at the site include a volunteer workforce and large amounts of birch and willow which are cut each year as part of the site management.

4 FLOATING WETLANDS: A REVIEW

4.1 What are floating wetlands?

Swarzenski et al (1991) used the term ‘floating marsh’ to refer to wetlands “**in which the floating mats of vegetation are thick enough to support a person’s weight**”. This is a common characteristic of floating wetlands worldwide: the ability to uphold the weight of a person has been commented upon in accounts of the *Sphagnum*-dominated ‘floating bogs’ of northern Europe and America (eg Lewis et al, 1928, in Alberta; French & Moore, 1986, on Llyn Mire in Wales), by Racine & Walters (1996) in describing sub-arctic floating mat fens in Interior Alaska, by Eggeling (1935) in relation to a tropical swamp in Uganda, by Kansime, Saunders & Loiselle (2007) in describing the floating papyrus and *Miscanthidium* swamps of Lake Victoria, by Hill et al (1987) in their account of floating raft vegetation on Australian billabongs and by Tyler (1976) in describing floating sedge mats on a Tasmanian lake. In Kawai Nui Marsh, Hawai’i, floating grass mats are described as supporting the weight of grazing cattle whilst ‘thick-mat’ floating marsh in the Mississippi delta (**Figure 3**) is described as “easily strong enough to support the weight of large animals”, in contrast to the more fragile ‘thin-mat’ vegetation (Sasser et al, 2007). This definition thereby excludes thin or ephemeral mats of floating vegetation, intermittently-floating sediment masses, aggregations of individual free-floating aquatic plants and emergent swamps of plants rooted to the shore or lake bed.

The sensation of walking on a floating wetland is sometimes compared to standing on a water bed or crossing a trampoline. The expressive German term *schwingmoor* (pl *schwingmooren*) is frequently used to describe specific types of floating mire in north-western Europe, including in Britain.

Usually, floating wetlands are sufficiently buoyant to rise and fall with changes in ambient water levels. This characteristic buffers them from the effects of both inundation and seasonal drawdown.

Ecological nomenclature for wetlands is notoriously variable and the proliferation of vernacular terminology for floating wetlands is liable to cause confusion. Quaking mires tend to be characterised by little upward vertical movement of the vegetation surface in relation to ambient water levels (Swarzenski et al, 1991) and the term often refers to terrestrial peatlands where the high water content of the substrate and the vegetation carpet nonetheless causes the mire surface to undulate when walked across. However, in floristic terms there is little to distinguish terrestrial quaking mires from *schwingmooren* which float over a deep column of free water, and the former may often represent the late stages in the infilling of basin mires formerly occupied by *schwingmooren*! Equally, quaking mires underlain by accumulated peat can occur towards the margins of basin mires where the central area is still occupied by a floating raft. The Irish term *scragh* or *scraw* can refer to both terrestrial and floating quaking mires and the European Union Habitats Directive uses a broad category of ‘transition mires and quaking bogs’ to encompass these types of wetland.

TABLE 4.1: Floating wetland terminology

battery	a peat mass rising to the surface in Okefenokee Swamp, Georgia or the Florida Everglades; the formation of a battery is known as a <i>blow-up</i> in Okefenokee
camalotale	floating vegetation raft of Amazonian river floodplains, also known as a <i>floating meadow</i>
embalsado	floating swamp, often dominated by <i>Cyperus giganteus</i> , formed in South American lakes and river deltas

floating bog	North American term equivalent to <i>schwingmoor</i>
floating mat	general term for floating vegetation structures
flotant	Louisiana term for floating vegetation in the Mississippi River Deltaic Plain
house	consolidated peat island developing from a battery, specific to the Okefenokee Swamp in Georgia (USA)
kragge	floating fen rafts on Dutch turbaries
phumdi (phoomdi)	floating masses of soil and vegetation unique to Loktak Lake, Manipur, India
pop-up	equivalent to <i>battery</i> , also a term restricted to the wetlands of the south-eastern USA
prairie tremblante	as <i>flotant</i>
quaking bog/fen/mire	general term for mire with an undulating surface when walked upon; includes floating formations but also terrestrial peatlands where the underlying substrate has a high water content
schwingmoor	can be used loosely in the same context as <i>quaking mire</i> but normally applied more strictly to peat-forming mires which float over a column of free water within a basin
Scragh	Irish term equivalent to <i>quaking mire</i>
Sudd	floating tropical swamp, usually dominated by <i>Cyperus papyrus</i> or <i>Miscanthidium</i> . Mainly used in an African context but occasionally more widely
turf pond	a peat cutting which becomes re-colonised by fen vegetation, often as a floating or semi-floating mat; specific to the East Anglian Broads
tussock	term for a floating vegetation raft specific to Florida lakes

4.2 Floating islands

Van Duzer (2004 & 2006) adopts a very broad definition of the subject of floating islands, encompassing buoyant natural and man-made substrates and temporary floating structures as well as raft-forming vegetation. For the purposes of the present report, it might be useful to define floating *islands* more narrowly as potentially mobile, buoyant features which are surrounded by water rather than being outgrowths of littoral vegetation. The present report focuses on buoyant, raft-forming wetland vegetation structures which include some floating islands but it is not concerned with islands per se.

Natural floating islands are relatively rare and typically form when masses of terrestrial peat are torn off by storms, or when the buoyant peat uplifts from the floor of basins following inundation (**Figure 4**). For example, the Floating Islands Lagoon at Pirron Yallock, Victoria (Australia) contains several visibly mobile peat masses supporting large trees. The lagoon basin is probably of volcanic origin but the islands appear to have developed following the flooding of swamp land after exceptionally high rainfall in 1952¹.

¹ <http://www.aussieheritage.com.au/listings/vic/Pirron%20Yallock/FloatingIslandsLagoonReserveProposed/15922>

4.3 Cultural significance of floating islands and floating wetlands

CG Munz (1711, in Van Duzer, 2004) cited references to floating islands by Roman scholars including Seneca in his *Naturales questiones*. Pliny the Younger described floating islands on Lake Vadimonis (now Lago di Posta Fibreno) in his *Naturalis historia*. A floating island known as La Rota still occurs on this calcareous lake fed by karstic springs at the base of the Apennine Mountains in Italy. An ancient type of fishing boat called a "nàue" was traditionally used to reach the island². Pliny also mentioned the floating reed islands of Lydia (now part of Turkey) which could be moved like punts using poles and provided refuge during the Mithradatic War. Much information on these early accounts of floating islands is provided by Van Duzer (2004), who has collated an extraordinary global bibliography containing references to floating islands in folklore, culture and science from Classical times onwards.

In the English West Midlands, floating bogs have their own folklore, with cautionary tales of water-sprites serving to warn children of the dangers of these places. Jenny Greenteeth was a widely-known water sprite, associated with a range of watery places, but Nellie Longarms was special to Wybunbury Moss in Cheshire (as recently retold by Bailey & Quigley, 2007).

4.4 Human usage of floating islands and vegetation rafts

Natural or artificial floating islands or rafts of vegetation have been used by people for various purposes (**Figures 5, 6, 7 and 8**). Floating-bed agriculture similar to hydroponics has been practised in several parts of the world since pre-history, and today occurs in Bangladesh, India, Burma and Cambodia. In Bangladesh, a *dhap* is a floating platform comprising heaps of decomposing water hyacinth used to grow vegetables and seedlings; *dhap* agriculture is practised mainly in common-property wetlands known as *khas* (Islam & Atkins, 2007). The 'floating' gardens or *chinampas* used by the Aztecs were first described by the Spanish explorer Acosta in 1590 (citation in Van Duzer, 2004). This ancient Mesoamerican form of agriculture uses wattle hurdles to fence in a plot of shallow water which is infilled with decaying vegetation and silt then used to grow maize and vegetables. The system is still in use in Mexico, although it is more akin to a raised-bed than a truly floating form of cultivation.

The culture of a few human populations is intimately bound up with floating rafts. Until very recently, the Ma'dan or Marsh Arabs of the Tigris-Euphrates Delta in southern Iraq used indigenous wetland resources in much the same way as early Mesopotamian peoples did in the 3rd Millennium BC (Ochsenschlager, 1998). The Ma'dan were traditionally semi-nomadic water buffalo herders who also caught fish, wild boar and waterfowl. They inhabited islands or floating platforms and used bitumen-coated reed canoes called *tarada*. The floating rafts of *Phragmites* provided platforms for large vaulted buildings (*mudhif*), smaller portable *raba* or *bat* buildings and winter shelters for water buffalo (*sitra*), all constructed from reeds (Ochsenschlager, 1998). In recent decades the Ma'dan suffered greatly from massive drainage of the wetlands (for both economic and social-control purposes), persecution and forced resettlement. Diversion of flows by dams in Turkey and Syria also affected the hydrology of the wetlands (Askari, 2003).

On Lake Titicaca in Peru, 41 floating islands are inhabited by members of the Uros, an indigenous pre-Inca tribe. The islands are artificial structures built from deep layers of *tatora* reeds (*Schoenoplectus californicus* ssp. *tatora*), which are regularly replenished. Upon these are constructed small settlements (also built of reed) and even watch towers. Originally used for defensive purposes, the floating islands are now a major tourist draw, with tourism income having replaced fishing as the means of subsistence for the population³.

² http://www.agri-net.org/parco_en.asp?idparco=35

³ See: <http://www.worldandi.com/public/2001/may/uros.html>; also references by Amat Quiroz and Antezana Bustinza cited by Van Duzer

Floating islands of papyrus (*Cyperus papyrus*) in Lake Kyoga, Uganda, are inhabited by local people whose livelihoods depend on the lake⁴. The papyrus is widely used for making mats, roofing thatch, fishing floats and rafts⁵. In the Lake Victoria wetlands, papyrus has significant economic importance as a material for craft products, roofing and fencing, paper production, cattle fodder and as a renewable energy resource. The high standing crop biomass means that harvesting of papyrus contributes to the removal of nutrients and C from the lake ecosystem, which is highly threatened by eutrophication from cities and other settlements around its shores (Kansiime, Saunders & Loiselle, 2007).

The floating *phumdi* of Loktak Lake, Manipur (India) support small populations of hut-dwellers and are also exploited by the wider lakeside communities. No less than 132 plant species associated with the *phumdis* are utilised for food, cattle fodder, fuel, thatching and hut construction, fencing, human and veterinary medicines, handicraft materials or for cultural purposes. Special fishing and fish harvesting systems (*phum* fishing and *athaphum* fishing) are associated with *phumdis* and account for 39% of the fish yield from the lake system (Trisal & Manihar, 2004).

The buoyant *embalsados* of the Paraná delta in Argentina are well-used by local hunters (Pratolongo et al, 2007) and it is likely that floating wetlands throughout the world have been used by local people as a source of waterfowl, fish and other foods.

4.5 Floating mires as a palaeoenvironmental resource

Peat-forming floating mires can provide an exceptional resource for palaeoenvironmental and environmental monitoring studies: “much of their own history, as well as the history of their surrounds, is recorded in the deposits of bog peat” (Hemond, 1980). The Thoreau’s Bog schwingmoor at Concord, Massachusetts, has been the subject of many scientific studies (eg Hemond, 1980; Hemond, 1983; McKnight et al, 1985; Fechner-Levy & Hemond, 1996; Rauch et al, 2004). Due to its undisturbed state, its simple ombrotrophic hydrology and lack of wave action, the bog raft provides “an outstanding monitor of environmental pollution” according to Hemond (1980).

Many palaeoenvironmental reconstructions of hydrosereal development have described the origins of floating wetlands or the peatlands which have succeeded them (eg Bellamy et al, 1966; Green & Pearson, 1977; Moore, 1978; Tallis, 1973). Often, such studies also shed light on environmental changes in the surrounding landscape (Bunting et al, 1998; Campbell et al, 1997; French & Moore, 1986; Magyari et al, 2001). Sediments held below the schwingmoor at Vankervelsvlei on South Africa’s Western Cape coast have preserved a palaeoenvironmental record spanning the past 40,000 years, rendering the site “one of the most complete late Quaternary records in southern Africa” (Irving & Meadows, 1997).

⁴ Lake Kyoga Integrated Management Project: <http://www.geo.uu.se/kyoga/kyoga.html>

⁵ World Lakes Database: Lake Kyoga: <http://www.ilec.or.jp/database/afr/afr-15.html>

5 FLOATING WETLANDS WORLDWIDE

Floating wetlands are widespread globally and form an important component of many wetland ecosystems.

In northern Europe, peat-forming rafts known as *schwingmooren* can develop over the surface of kettle-hole lakes (**Figure 9**). Similar wetlands have developed in mountain lakes and lowland oxbows south to the Pyrenees and north-eastern Hungary. Floating fen mats also develop over turbaries (peat cuttings), as in the turf ponds of the Norfolk Broads and the *kragge* fens of the Netherlands. The *plaur* of the Danube Delta (Romania/Moldavia) are floating *Phragmites* rafts covering around 1,000 km².

Floating wetlands are widespread in the Americas, from the sub-arctic to the tropics. Floating rafts of vegetation characterise sub-arctic groundwater-discharge fens in the Tanana Flats, Alaska, covering around 100 km². In Canada and northern USA, boreal and temperate floating mires are much more frequent (and much better studied) than in Europe. Further south, vegetated floating peat rafts known as batteries or pop-ups are important features of the Okefenokee Swamp in Georgia (USA) and the Florida Everglades. Recent studies suggest that there may be as much as 160,000 ha (1,600 km²) of floating wetland in the Mississippi River Deltaic Plan, although the extent of maidencane-dominated 'thick-mat' flotant is declining (Sasser et al, 1996). *Camalotes* are masses of floating vegetation which form consolidated rafts in the floodplains of Amazonia. In the lagoons and deltas of tropical and temperate South America, sedge rafts known as *embalsados* can cover extensive areas.

Floating papyrus swamps form part of the huge *Sudd* floodplain wetlands of the White Nile in southern Sudan. These are also an extensive feature of the Lake Victoria ecosystem, the Zambezi Delta in Mozambique and the Okavango Delta in Botswana. Some of these floating swamps cover hundreds of square kilometres.

Floating wetlands appear to be less frequent in Asia but buoyant masses of vegetation and sediment known as *phumdis* cover 135 km² of Loktak Lake in Manipur (India).

Floating swamps occur on volcanic crater lakes in Queensland, Papua New Guinea and on Easter Island. Rafts of aquatic grasses occur extensively on some oxbow-type billabongs in the Northern Territories of Australia.

5.1 Northern floating mires

In many boreal peatlands such as the Canadian *muskeg*, quaking mire develops over infilling basins (often kettle-holes). Lewis et al (1928) described a raft of *Menyanthes trifoliata*, rooted in the shoreline sedge mat but extending out onto the lake surface, as initiating terrestrialisation in a muskeg lake in central Alberta. In a slough (kettle-hole) near Edmonton they described a floating mat dominated by *Scolochloa festucacea* and *Carex atherodes*, forming a band 15 m wide around the margin of the open water. The same authors describe quaking mats in the central areas of infilled sloughs as characterised by *Hypnum* mosses, *Menyanthes* and sedges, especially *Carex magellanica*. Associated species included *Potentilla palustris*, *Cicuta maculata*, *Carex chordorrhiza*, *C. diandra* and the cotton-grass *Eriophorum chamissonis*. This community bears resemblance to the M9 *Carex rostrata* – *Calliargon* moss mire described in the British National Vegetation Classification (Rodwell, 1991).

In Labrador, Foster & King (1984) describe the zonation of floating mats of vegetation fringing tarns in the Leech Lake Peatland. At the open water interface, there was a 0.5 to 3.0 m wide zone of *Carex rostrata* and the water-lily *Nuphar variegata*, *Sparganium angustifolium* and the bladderwort *Utricularia intermedia*: the mat produced by this vegetation "is submerged and only

loosely maintained by an open network of sedge rhizomes”. Behind this is a more consolidated mat of *Carex limosa* and *Menyanthes* rhizomes over aqueous peat debris. A rather similar riparian floating mat community has been reported elsewhere in Labrador, characterised by an outer fringe of *Calla palustris* and *Menyanthes trifoliata* with *Carex limosa*, *C. rostrata*, *Cicuta bulbifera* and *Lysimachia thrysiflora* in the sedge mat (Allen et al, 2004).

Foster & King also note that *Carex rostrata* commonly forms a loose floating mat on the open water of oligotrophic lakes in Labrador, with paleobotanical evidence indicating that this mat can develop into a consolidated raft, trapping peat and allowing colonisation by *Sphagna* then ericaceous shrubs.

Floating mires extend northwards into the sub-arctic zone in North America, eg in northern Quebec (Roulet, 1991). Racine & Walters (1994) and Racine et al (1998) have described an apparently unique form of sub-arctic fen raft from the Tanana Flats in Alaska. Covering around 100 km², these fens are fed by circumneutral and relatively nutrient-rich groundwater emanating from the base of the adjacent uplands and discharging towards the Tanana River along ill-defined channels across flats of alluvial sediments. A dense, fibric mass of rhizomes and peat 0.5 to 1.0 m deep is either grounded or, more often, floats over clear water or ooze 1.5 to 2.5 m above the substratum. Racine & Walters (1994) describe four types of floating mat plant community:

- *Menyanthes trifoliata* stands, either monodominant or with *Carex aquatilis*, *Potentilla palustris* and *Equisetum fluviatile*
- *Carex aquatilis* stands, with *Equisetum fluviatile* and *Potentilla palustris*
- *Typha latifolia* stands with an understorey of *Menyanthes*
- *Calla palustris* stands with *Hippuris vulgaris*, *Bidens cernua* and *Calamagrostis* spp; these semi-aquatic communities are restricted to peripheral ‘moat’ areas

Other associated species include *Carex lasiocarpa* and *Cicuta virosa* with occasional woody plants but mosses are “conspicuously absent”. There is no obvious topographical patterning of the vegetation (as seen in terrestrial northern peatlands). The floating mats can support a person’s weight with a deflection of 0.1 to 0.5 m. *Menyanthes*-dominated rafts with little peat accumulation show the greatest deflection whilst sedge-dominated rafts with the greatest peat content and lowest water content show the least deflection.

TABLE 5.1: Characteristics of floating fen mats in the Tanana Flats, Alaska
(based on Racine et al, 1998 and Racine & Walters, 1994)

Raft thickness	50-100 cm
Peat content	40% dry weight
Mineral content	<10% in upper 30 cm C. 25% in lower half
Specific gravity (at 10-20 cm depth)	0.12 - 0.18 g cm ⁻³ dry weight 0.80 - 0.95 g cm ⁻³ wet weight
Surface water pH	6.7
Surface water electrical conductivity	350 μS cm (270-400 μS cm)
Height of herbaceous overstorey	50-100 cm
Standing crop biomass	10 kg m ²
Water flow rate	0-5 cm/s ⁻¹ , average of c. 2 cm/s ⁻¹

5.2 *Schwingmoor* and floating bog

Schwingmoor develops as mire vegetation spreads centripetally over the surface of small lakes (Tallis, 1973). In some cases, the bog may comprise a peat raft several metres thick floating over a considerable depth of water. *Schwingmooren* (known as ‘floating bogs’ in North America) are usually associated with kettle-hole type depressions, where ice blocks embedded in the till during glacial periods have left abrupt, steep-sided basins. Such features are, therefore, associated with formerly glaciated regions of North America and northern Europe. In the USA, north-eastern Ohio marks the southern limit of kettle-hole basins with their associated floating mires (Andreas & Bryant, 1990). In Europe, the Hortobágy National Park in north-eastern Hungary appears to represent the southern limit of peat-forming floating mires, although these develop in oxbows rather than kettle-holes (Nagy et al, 2007).

The association between *schwingmoor* formation and kettle-hole basins is probably due to their morphology, which allows the development of floating, peat-accumulating mire with a long time-lag before the underlying waterbody infills with sediment and the mire becomes terrestrialised. Two English *schwingmooren*, Wybunbury Moss and Chartley Moss are probably associated with sink holes created by the dissolution of underlying saliferous deposits (Tallis, 1973; Green & Pearson, 1977). There are also rare examples of *schwingmoor*-type floating mires developing in inter-dunal basins as at Vankervelsvlei on the Western Cape coast of South Africa (Irving & Meadows, 1997). Shank Painter Bog on the Cape Cod coast (Massachusetts) is claimed to be “the largest quaking bog known to exist in a barrier beach / coastal dune ecosystem worldwide” (Town of Provincetown, 2000).

5.3 British *schwingmooren*

Schwingmooren comprise a floating raft of peat covered by mire vegetation. The dominant *Sphagnum* vegetation with its associated bog flora and partly ombrotrophic (rain-fed) hydrology represents a mature stage in the hydrosere and will usually have developed on top of a pioneering sedge raft in contact with the groundwater. The English West Midlands (Cheshire, Staffordshire, Shropshire) has numerous kettle-holes and the meres and mosses of this region represent the main concentration of *schwingmooren* in Great Britain. The West Midlands Mosses Special Area of Conservation (SAC), considered to contain the prime examples of *schwingmoor* in Britain, contains only around 65.4 ha of mire vegetation spread over 3 sites, of which only 44.6 ha is classified as quaking bog (based on SAC data sheet⁶), suggesting that *schwingmoor* is very rare in Britain⁷. However, other *schwingmooren* have been reported and these mires form components of more extensive wetland habitats: for example, Chartley Moss, covering 106 ha, is the largest basin mire in England (Ratcliffe, 1977b).

Wybunbury Moss is a classic *schwingmoor* on the Cheshire Plain, with a raft of peat up to 4.5 m deep covering most of the basin, floating over 14 m of water (Green & Pearson, 1968 & 1977; Ratcliffe, 1977b). The raft is dominated by the bog moss *Sphagnum recurvum* with smaller amounts of *S. papillosum*, *S. rubellum* and other mosses; vascular plants include *Vaccinium oxycoccus*, *Eriophorum angustifolium*, with small amounts of *Drosera rotundifolia*, *Andromeda polifolia* and *Calluna vulgaris* (English Nature, 1986). Small *Pinus sylvestris* (Scots pine) trees are common but once they reach 2 m height they begin to sink into the mat and drown. The peat raft rises and falls with the watertable, maintaining fairly stable moisture levels in the *schwingmoor*, with wet conditions in summer inhibiting tree establishment. On the margins of the Moss there is a transition to drier mire vegetation and where the peat is firmly consolidated,

⁶ Accessible at www.jncc.gov.uk/ProtectedSites/SACselection/n2kforms/UK0013595.pdf

⁷ Based on <http://www.jncc.gov.uk/ProtectedSites/SACSelection/sac.asp?EUCode=UK0013595>

birch woodland is established (English Nature, 1986). Evidence of eutrophication has been known for some time in this mire system (Ratcliffe, 1977a).

The *Sphagnum*-dominated raft at Wybunbury Moss is very acidic (mean water pH = 3.65) due to cation exchange by the dominant mosses; free water below the mat is circumneutral (pH 6.55-7.20) (Green & Pearson, 1968). An assessment of current hydrological and water quality issues at Wybunbury Moss is provided by Hawley et al (2004).

At the Abbot's Moss complex in Cheshire, the predominant vegetation of the schwingmoor is the *Sphagnum recurvum*-dominated form of the *S. cuspidatum* - *S. recurvum* bog-pool community, coded M2a in the National Vegetation Classification (NVC: Rodwell, 1991-2000) (Ecological Services UK, 2006). The *Rhynchospora alba* (white beak-sedge) subcommunity (M2b) is a more localised component of the schwingmoor as is *Carex rostrata* – *Sphagnum recurvum* mire (NVC M4).

Chartley Moss in Staffordshire covers around 25 ha and, in parts, supports a 3 m thick raft floating over a basin at least 9 m deep; two large pools are believed to be contiguous with the underlying reservoir of water (Ratcliffe, 1977b). The open schwingmoor is dominated by *Sphagnum recurvum* with associated species much the same as at Wybunbury. There is a transition to stunted *Pinus sylvestris* woodland on consolidated peat and *Betula pubescens* - *Quercus robur* woodland on dry, solid peat (**Figures 10 and 11**).

Clarepool Moss in North Shropshire is a basin mire which has at least partly developed as schwingmoor, although open, quaking *Sphagnum* mire is now of restricted distribution and much of the site comprises bog woodland (Nature Conservancy Council, 1983). The site does, however, contain an open pond representing the last area of open water in the hydrosere (Ratcliffe, 1977a).

Llyn Mire in Central Wales contains twin basins, the southern one supporting schwingmoor consisting of a *Sphagnum* lawn with *Rhynchospora alba* and *Vaccinium oxycoccus*; this has been described as a "classic schwingmoor" (French & Moore, 1980). The northern basin has been cut-over for peat in the past and has been recolonised by a floating poor-fen raft of *Eriophorum angustifolium*, *Carex rostrata*, *Potentilla palustris* and *Sphagnum recurvum* (Ratcliffe, 1977b).

Elsewhere in Britain, the eastern 'moss' of the kettle-hole complex at Silver Tarn SSSI, Cumbria, has been described as a thin schwingmoor mat overlying open water or aqueous peat (Hawley et al, 2004). Muckle Moss in Northumberland has also been described as a "particularly good example of a *Sphagnum*-dominated schwingmoor", albeit within a valley mire (Ratcliffe, 1977a). Lord's Lot Bog near Carnforth in Lancashire has also been described as a *schwingmoor*⁸.

Floating *Sphagnum* mire occurs on the site of a groundwater-fed valley lake at Shortheath Common SAC in Hampshire; the floating mat here appears to be quite young (as indicated by the lack of peat deposition below) and probably developed following human modification of the basin's hydrology (Allen, undated). Floating mat development is a feature of Blaencamlais Pond on Mynydd Illtyd SSSI in Powys, Central Wales.

The distribution of floating mires in Scotland is unclear. Wells (2001) described a mire at Pitmaduthy in the Highlands as incorporating extensive areas of floating *Sphagnum* carpet. Acton (2004) documented an example of floating *Sphagnum palustre* bog with abundant *Carex rostrata* and lesser amounts of *Menyanthes trifoliata* and *Eriophorum* at Clais Dhearg SSSI in Argyll. It is suspected that similar features will be relatively widespread in Scotland.

⁸ http://www.lancswt.org.uk/Our%20Reserves/lord's_lot_bog.htm

Within Yorkshire, quaking mires occur in a number of situations. Sometimes, as at Throxenby Mere (Scarborough), complete vegetation cover has developed over aqueous peat and comprises rhizomatous species such as *Potentilla palustris* and *Carex rostrata* carpeted by a deep layer of more base-tolerant *Sphagna*. Whether this should be classified as a *schwingmoor* or a *kragge/scragh* mire is unclear.

In Ireland, semi-floating *scragh* is a widespread component of peatland habitats and is occasionally described as *schwingmoor*, eg Fairy Water Bogs Ramsar Site in County Tyrone. O'Mahony (2001) describes the margins of Lough Pole in County Cork as covered by a dense, floating mat of intermixed *Menyanthes trifoliata*, *Carex rostrata*, *Typha latifolia* and *Sparganium erectum*. At Lough Duff in Connemara, the lake is fringed by a quaking raft of vegetation dominated by *Sphagna*⁹.

5.4 North American floating bogs

There is considerable similarity between North European *schwingmooren* and the 'floating bogs' of North American kettle-holes and the two are functionally equivalent. Floating bogs develop from pioneer rafts to peat-forming, *Sphagnum*-dominated mires (sometimes with more basiphilous fen vegetation at the margins). The flora of the *Sphagnum* mat includes many species in common including cranberries (*Vaccinium* spp.), bog rosemary (*Andromeda polifolia*, = *A glaucophylla*), sundews (*Drosera* spp) and sedges such as *Carex limosa*.

In northern USA, floating bogs occur in Maine, New Hampshire, Vermont, Massachusetts, New York, New Jersey, north-eastern Ohio, Michigan, Indiana, Minnesota, Wisconsin, Montana, Wyoming, Idaho and Oregon (eg Andreas & Bryant, 1990; Lynn, 1984; Robichaud Collins & Anderson, 1994; Natural Heritage Advisory Council, 2003; NPWRC, 2006; Swineheart & Parker, 2002; Wilcox & Simonin, 1988). Floating mats of *Menyanthes trifoliata*, *Potentilla palustris*, *Carex limosa*, *Sphagnum squarrosum* are also reported to occur at Grass Lake in the Sierra Nevada, California¹⁰.

The hydrology of North American floating mires apparently varies from site to site. Mature floating bogs in enclosed basins can become fully ombrotrophic (fed by rain alone), eg Thoreau's Bog in Massachusetts (Hemond, 1980). The development of ombrotrophic conditions may depend on whether the climate is humid enough (Bunting & Warner, 1998). In Ohio, nutrient run-off from higher ground surrounding kettle-holes limits the shift to ombrotrophy in *Sphagnum*-dominated basin mires (Andreas & Bryan, 1990). This situation is not dissimilar to English *schwingmooren* where catchment inputs counteract the development of purely ombrotrophic conditions (Ratcliffe, 1977a, Hawley et al, 2004).

5.5 Other North American floating wetlands

Bowles & Jones (2006 & 2007) refer to 'calcareous floating mat' fens in the Chicago region, dominated by *Calamagrostis canadensis* and *Carex lasiocarpa* with *Scirpus validus* and *Carex aquatilis* also abundant. Associated species include *Lysimachia thrysiflora*, *Aster borealis* and *Thelypteris palustris*. During the period 1976-2002, *Typha* species and non-native plants increased in these wetlands although overall species composition had changed little. Although this type of fen extends into Wisconsin, it appears to be largely restricted to the State of Illinois, with around 169 acres (68.4 ha) within the Chicago Wilderness Area (Chicago Wilderness Consortium, 1999).

⁹ NHA citation, accessed at www.npws.ie/en/media/Media.4327.en.pdf

¹⁰ USDA Forest Service, Pacific Southwest Research Station: Research Natural Areas information, accessed at: http://www.fs.fed.us/psw/programs/rna/gtr_chapters_pdf/grass_lake_rna.pdf

Floating-mat 'sedge meadows' or *Calamagrostis*-dominated fens have also been described from Waunakee Marsh in Dane County, Wisconsin (Bedford et al, 1974).

The term shore fen is applied to wetlands on the shorelines of the Great Lakes in North America. The term is sometimes used simply to denote a littoral wetland but it is also used specifically to refer to a floating sedge mat in the zone where streams enter the lakes (Judziwicz, 2001). Along the shore of Lake Superior, shore fens are typically separated from the open lake by a sand spit. The vegetation is dominated by *Carex lasiocarpa*, *Menyanthes trifoliata* and the shrub *Myrica gale*. A wide range of associates occur including *Cladium mariscoides*, *Sium suave* and *Equisetum fluviatile*. The Minnesota Native Plant Community classification includes a similar 'Northern Shrub Shore Fen' associated with the inland zones of floating mires. This is characterised by woody plants such as *Chamaedaphne*, *Betula pumila* and *Salix pyrifolia*, minerotrophic Sphagna, and the herbs *Potentilla palustris*, *Lysimachia thrysiflora*, *Carex lacustris* and *Thelypteris palustris*. A similar community (*Betula pumila* – *Calamagrostis canadensis*) has been reported from a riparian floating mat in Alberta (Allen et al, 2004).

Box 1: Attributes of calcareous floating-mat fen in Illinois (Extract from: *Chicago Wilderness Region Biodiversity Recovery Plan*. Accessed at <http://www.epa.gov/ecopage/gldb/cwplan/>)

Calcareous floating mat. This community exists as a thin, floating bed of peat in glacial lake basins. Diffused calcareous seepage from bordering upland and fire created this community from graminoid bogs, which it resembles in composition. The mat supports a tall matrix of sedge and grasses, low-statured boreal relict shrubs and boreal herbs, and in some cases, calcophiles typical of graminoid fens.

Dominant plants: *Calamagrostis canadensis*, *Carex aquatilis* var. *elatior*, *Carex lasiocarpa*, *Carex prairea*

Characteristic plants: *Aster borealis*, *Hypericum virginicum fraseri*, *Menyanthes trifoliata*, *Potentilla palustris*, *Salix candida*, *Salix pedicellaris*, *Utricularia intermedia*

Characteristic animals: Swamp Sparrow

Floating mats dominated by *Decodon verticillatus* occur quite widely in kettle-holes and, more rarely, artificial basins in North America. For example, floating *Decodon* rafts dominate a number of kettle-hole ponds in Alley Pond Park in New York City¹¹. At one Wisconsin site, *D. verticillatus* was described as "Forming lake edge floating mat with *Typha*, also with *Scirpus fluviatilis*, *Lemna minor*, *Menyanthes*, *Mnium* and *Eleocharis*"¹².

5.6 Raft-forming vegetation of shallow basins

The Irish term *scraw* (anglicised from *scragh*) refers to quaking mats of peatland vegetation (Wheeler & Proctor, 2000); the term encompasses *schwingmoor* but also covers a range of terrestrial mires. In the Republic of Ireland, wetlands classed as 'transition mire and quaking bog' (an EU Habitats Directive category) are estimated to cover 1,955 ha (Foss, 2007) but this includes *scragh* communities of wet hollows, terrestrialised basins and open water transitions so no figure for floating formations is specified. These communities are characterised collectively by extensive moss cover (typically dominated by Sphagna, *Calliergon* spp. or *Scorpidium*) with

¹¹ http://nycgovparks.org/sub_your_park/historical_signs/hs_historical_sign.php?id=11313

¹² Wisconsin Botanical Information System (Wisconsin State Herbarium):
<http://botany.wisc.edu/wisflora/specimen/scripts/specimen.asp?accession=v0053702WIS>

vascular plants such as *Carex diandra*, *C. lasiocarpa*, *C. limosa*, *Menyanthes trifoliata*, *Hydrocotyle vulgaris* and *Potentilla palustris*.

Crushell et al (2006) describe *scragh* invading an open water 'soak' fed by calcareous groundwater within a predominantly ombrotrophic bog. The most aquatic stage is characterised by *Utricularia minor*, *Hydrocotyle vulgaris* and *Carex rostrata* along with the aquatic moss *Warnstofia fluitans*. This is followed by mats of *C. rostrata*, *Menyanthes trifoliata* and *Sphagnum fallax* or *C. rostrata* and *Potentilla palustris* with a deep bryophyte layer. As the soak becomes infilled with vegetation, the minerotrophic vegetation rafts are invaded by bog species.

In the context of upland mires in New South Wales, Australia, Millington (1954) uses the term scraw to describe "a raft of Sphagna and unconsolidated peat, dominated by low sedge and/or restionaceous plants, floating on semi-liquid ooze derived from earlier aquatic and reed swamp stages".

5.7 *Kragge* fens and turf ponds: fen rafts in turbaries

Floating or semi-floating rafts of fen vegetation have been documented from turbaries (shallow peat cuttings) in Britain, the Netherlands and central Russia. Similar formations probably occur on other cut-over northern peatlands.

In the Netherlands, formation of a floating raft is an important successional pathway in steep-sided turbaries, which vary from 70 to 250 years old. Typically, the raft comprises a 40 cm deep mat of living and dead roots and peat over a lens of free water or watery detritus (Verhoeven et al, 1988). These quaking fens or *kraggen* are particularly rich in rare vascular plants and bryophytes but represent a relatively short-lived stage and require active management (such as mowing) to inhibit succession (Van Wirdum, 1995). In the absence of management, the herbaceous fens are eventually replaced by a type of fen-woodland dominated by *Alnus glutinosa* (alder) and *Betula pubescens* (downy birch) (Wieggers, 1990).

Van Wirdum (1995) recorded that there are around 12,000 ha of terrestrialising turbaries in the Netherlands but only around 100 ha support the *Carex lasiocarpa* community typical of *kragge* fen. He describes various modes of *kragge* formation:

- Encroachment from the margin
- Flotation of bottom peat or loose sods
- Secondary colonisation of masses of free-floating aquatic plants (such as *Stratiotes aloides*, water soldier)
- Bottom-rooted *Phragmites* forming adventitious roots which develop into a raft, or uplifting of *Typha angustifolia* swamp initially established on the pond bottom

He notes that, "A period of some tens of years may be needed for *kragge* formation...Aquatic vegetation in the lake phase may be helpful but is not a *conditio sine qua non*." The initial swamp phase of raft formation is characterised by tall species such as *Typha angustifolia*, *Phragmites australis*, *Schoenoplectus tabernaemontani*, *Cicuta virosa*, *Menyanthes*, *Equisetum fluviatile* and *Carex* spp.

At Catfield and Irstead fens in the Norfolk Broads, Giller & Wheeler (1986) suspected that buoyant root mats of *Typha* and *Phragmites*, loosely rooted in the substratum and often uplifting, played a role in the successional development of shallow 19th century peat cuttings, analogous to the *kragge* described from Dutch turbaries.

Wheeler & Shaw (1995) describe further the successional process in turf ponds. The uplifting or detachment of bottom-rooted plants appears to be an important initial mechanism, apparently

due to gas production in the flooded peat. Subsequently, the ability of the mat to move up to 50 cm vertically profoundly affects the colonising vegetation “by acting as a ‘hydrostat’ which helps to minimise fluctuations of water level relative to the peat surface, thus avoiding substantial surface drying or deep inundation”. As in the Netherlands, such conditions appear to be particularly favourable for a number of rare fen plants.

However, leaching of minerals in the raft by rainwater can lead to acidification and the development of *Sphagnum*-dominated vegetation. Van Diggelen et al (1996) estimated that a 40 cm deep vegetation mat could become completely decalcified within a period of around 30 years. Acidification was precipitated when build-up of sediment below the raft inhibited the circulation of base-rich groundwater. Giller & Wheeler (1988) have described the development of ‘embryonic bog’ on turf ponds in a Broadland floodplain fen within a timescale of 150 years.

Loss of the rich-fen stages of *kragge* fen is a serious concern for some Dutch conservationists and there has been considerable research into eco-hydrological measures to reverse acidification (Beltman et al, 1995, 1996, 2001; Bootsma et al, 2002; Dekker et al, 2005). A combination of sod removal and surface drainage (to divert accumulated rainwater and allow irrigation by base-rich surface water) appears to be required to shift *Sphagnum*-dominated rafts back towards rich-fen assemblages (Beltman et al, 1996).

In central Russia, Kutz (1926) documented vegetation succession in turbarry pits. Succession was eventually to a *Sphagnum – Eriophorum vaginatum* quaking mire in 30 year old cuttings. In more base-rich pits, initial colonisation was by aquatic macrophytes including *Equisetum fluviatile*, whose rhizomes “give the bog plants a substratum on which they can fix themselves”. Very often the colonisation of *Equisetum* was accompanied by the spreading of a mossy carpet over the water surface, typically formed by *Hypnum aduncum* and *Sphagnum teres*. This eventually succeeded to a transition fen of *Carex rostrata* and *C. lasiocarpa*. Other turbarries were colonised from the edges by floating *Sphagna* and *C. rostrata*, forming rafts covering hundreds of square metres.

Van Wirdum notes that *kragge* have formed in oxbows as well as turbarries, so this vegetation formation is not restricted to artificial basins. Similarly, Somodi & Botta-Dukát (2004) describe a range of floating-mat fen communities present in oxbows adjoining the River Danube south of Budapest. Floating, peat-forming mires also occur in oxbows in the Hortobágy National Park in north-eastern Hungary (Nagy et al, 2007).

Floating or semi-floating rafts are occasionally associated with old clay workings. At Eastington Ponds near Howden (East Yorkshire), one of a series of railway borrow pits has been colonised by a raft of *Typha angustifolia*, over which has developed a deep moss layer: at the edges, in contact with the water, this includes *Calliergonella cuspidata* and other basiphilous species but the centre is dominated by a thick layer of *Sphagnum* which creates acidic conditions (Hammond, 2007b).

In an abandoned silica sand quarry in Ohio, minerotrophic *Sphagnum* mire dominated by *S. teres* and *S. recurvum* developed within 70 years over a framework of *Typha latifolia* to form a semi-floating mat with a mean depth of 30 cm (Andreas & Host, 1983). An exceptionally high rate of peat accumulation was noted in this habitat. The colonisation of key plant species was probably facilitated by the presence of a nearby mire during the operational life of the quarry since a younger quarry nearby with apparently similar conditions has not developed mire vegetation.

5.8 Floating temperate reedswamps

Floating fringes of reedswamp, known locally as *hover*, occur commonly on the Norfolk Broads (Wheeler & Proctor, 2000). Lambert (1946) described the dynamic relationship between rooted *Phragmites* reedswamp and floating *Glyceria maxima* (reed sweet-grass) 'hover'. The floating *G. maxima* mat was protected by an offshore fringe of *Phragmites*. Below the hover, autogenic peat accumulates; towards the inland edge of the raft, build-up and compaction of hover peat, together with deposition of tidal mineral sediments, establishes the conditions for terrestrial fen.

The *plavy* (in Ukrainian) or *plaur* (Romanian) of the Danube Delta (Romania and Moldavia) is the most extensive form of floating reedswamp in Europe, covering around 1,000 km²¹³. Hanganu et al (2002) document the largest single vegetation unit in the Danube Delta as *Phragmites* vegetation on compact *plaur*, covering 37,270 ha. Their inventory also includes 'reed vegetation and trees on compact *plaur*' (11,830 ha), 'reed vegetation on open *plaur*' (27,573 ha) and 'reed vegetation and trees on open *plaur*' (6,552 ha).

The structure of the *plaur* was summarised by Anon (1917), based on the researches of Marietta Pallis. It is a "compact raft-like structure from 8 cm to 2 m in thickness, composed of the interlaced rhizomes of reed closed together by numerous roots, which retain much soil and thus completely fill the interstices between the rhizomes". The *Phragmites* growing on the *plaur* can be 5 m, exceptionally even >7 m high. In deeper water, ramifying vertical branching is abundant, forming a tussock-like structure which detaches from the substratum as basal rhizomes die-off to form the floating raft. *Thelypteris palustris* (marsh fern) is abundant below the reed canopy and, as the *plaur* matures, additional species such as *Cladium mariscus*, *Typha angustata* and *Carex riparia* colonise. Van Wirdum (1995) states that some Romanian *plaur* are believed to be thousands of years old.

Kłosowski (1993) described a floating Thelypteridi-Phragmitetum swamp fronting riparian alder woods in the Mazurian lake district of north-east Poland. This functions like a riparian 'hover' community. Floating mats of *Carex lasiocarpa* have been reported as forming a narrow fringe of hover along the Thompson River in Montana (Greenlee & Jones, 2000).

Typha species are common dominants in temperate and subtropical floating swamps. The account of *Typha* communities in the Maryland (US) vegetation classification refers to their occurrence in the floating-mat zones of littoral swamps¹⁴. In a survey of wetland vegetation at Kiser Lake State Park, Ohio, Neff & Vankat (1982) describe a "herbaceous floating meadow" composed of a dense mat of herbs and mosses characterised by *Typha latifolia*, *Eupatorium perfoliatum*, *Sagittaria latifolia* and *Equisetum* sp. Segadas-Vianna (1951) described *Typha* spp. as forming floating mats in Michigan, but only along the edges of flowing water; his paper is illustrated with a photograph of such vegetation from the Huron River. Floating rafts formed from the interlaced rhizomes of *Typha angustifolia* cover extensive areas of the 970 ha Lake Žuvintas biosphere reserve in Lithuania¹⁵.

Floating reedswamp communities can provide platforms for bog development, although this is perhaps a less obvious pathway than *schwingmoor* formation. Krusi & Wein (2004) postulated that as floating *Typha* mats expanded across a Canadian impoundment lagoon, the reduction in water temperature (due to increased insulation from summer warming) would slow decomposition and nutrient-turnover rates. This they expected to result in declining *Typha* dominance and invasion of the mat by *Sphagnum*, evidence of which was already present in

¹³ Based on the United Nations Environment Programme datasheet accessed at: <http://www.unep-wcmc.org/sites/wh/danubed.html>

¹⁴ http://www.dnr.state.md.us/wildlife/Md_Veg_Com/93_.asp

¹⁵ <http://www.zuvintas.lt/en>

localised areas about 10 years after the floating-mats first developed. Hogg & Wein (1988b) recorded a successional trend towards poor fen in some areas on this floating mat, where *Typha* vigour had declined and *Carex limosa*, *Drosera rotundifolia*, *Vaccinium macrocarpum* and *Sphagna* have become locally abundant. This was accompanied by a biogenic reduction in pH at the mat surface. The formation of a *Sphagnum* raft overlying semi-floating *Typha angustifolia* swamp in a eutrophic borrow pit in East Yorkshire has been documented by Hammond (2007b).

5.9 Raft-forming mires in the British National Vegetation Classification

The British National Vegetation Classification describes five wetland communities or sub-communities which can form floating or semi-floating rafts. Most of these combine an abundance of herbs with buoyant, ramifying rhizomes and a deep moss layer. The key herbs appear consistently to be *Carex rostrata*, *Menyanthes trifoliata* and *Potentilla palustris*. These communities all have *Carex rostrata* as a dominant or abundant species and represent a floristic gradient from species-poor swamp (S9, S10b) to species-rich tall-herb fen (S27), and also an edaphic gradient from base-poor (M5) to base-rich (M9) conditions. Long-established schwingmooren support *Sphagnum*-dominated mire vegetation similar to that of raised bogs (eg NVC M2: *Sphagnum recurvum* mire).

NVC S9 *Carex rostrata* swamp develops in shallow, oligotrophic to mesotrophic standing waters, usually with organic substrates (Rodwell, 1995). The *Menyanthes trifoliata* – *Equisetum fluviatile* subcommunity (S9b) sometimes develops as a floating mat containing *C. rostrata*, *M. trifoliata*, *Potentilla palustris* and *E. fluviatile*.

NVC S10b *Equisetum fluviatile* swamp (*Carex rostrata* sub-community) is dominated by the aquatic horsetail *E. fluviatile* intermixed with *C. rostrata*, *Menyanthes* and *Potentilla palustris* (which can occasionally dominate). This vegetation characteristically forms a mat “which sometimes occurs as a swinging, semi-submerged vegetation” (Rodwell, 1995).

NVC M5 *Carex rostrata* – *Sphagnum squarrosum* mire is associated with “...mildly acidic, only moderately calcareous and rather nutrient poor waters” (Rodwell, 1991):

“Quite commonly, the vegetation occurs as a floating mat bound together below by the robust rhizomes of *Carex rostrata*, *Potentilla palustris* and *Menyanthes*, which can grow very vigorously in the aquatic environment, and then the raft may rise and fall with fluctuations in the water level.”

NVC M9 *Carex rostrata* – *Calliergon* spp. mire is found in rather more mesotrophic conditions but also has abundant *Potentilla palustris* and *Menyanthes*. Rodwell notes that, “These species probably play an important part in the establishment of the floating rafts in which form this vegetation is often found...” He also states that,

“...the vegetation often develops as a floating or semi-floating raft which can rise and fall with any change in water level, as the typically unconsolidated deposits beneath expand and contract: this tends to reduce the amplitude of the variations relative to the surface and maintains a fairly consistent hydrological and redox environment.”

Furthermore: “Under certain conditions, it is...possible that succession [from this community] tends not to be to mire forest but ultimately to ombrogenous bog”.

Similar vegetation structure also characterises NVC S27 *Carex rostrata* – *Potentilla palustris* tall-herb fen.

Table 5.2 summarises the floristic and ecological characteristics of raft-forming fen communities

identified in the NVC. In addition to these communities, the *Glyceria maxima* subcommunity of *Glyceria maxima* swamp (S5a) can occur as a fringing 'hover' in the East Anglian Broads (Lambert, 1946) but this reflects the unusual conditions of the lower Yare valley (Rodwell, 1995). *Typha angustifolia* swamp (S13) can also occur as a floating mat. The Joint Nature Conservation Committee website describes the *Eriophorum angustifolium* bog-pool community (NVC M3) as being associated with schwingmoor development on dystrophic pools within the West Midlands Mosses SAC but is unlikely that *E. angustifolium* is a primary mat-forming species.

A distinct category of *Menyanthes - Potentilla palustris* rafts is recognised in the European Environment Agency's classification of vegetation types (coded D2.39)¹⁶. This is characterised by *Menyanthes*, *P. palustris* and *Hydrocotyle vulgaris* often with *Equisetum fluviatile*, *Carex rostrata*, *Cicuta virosa* and various Sphagna and/or 'brown' mosses.

TABLE 5.2: Raft-forming mire communities in the National Vegetation Classification¹⁷

Community	Constant species	Frequent species	Water depth range	Water chemistry	Substrate
S9b: <i>Carex rostrata</i> swamp (<i>Menyanthes trifoliata</i> – <i>Equisetum fluviatile</i> subcommunity)	<i>Carex rostrata</i> , <i>Equisetum fluviatile</i> , <i>Menyanthes trifoliata</i>	<i>Potentilla palustris</i>	+2 to +40 cm (mean ca. +20 cm)	pH 5.0 – 6.8, oligotrophic to mesotrophic waters	Organic (less often silty or sandy)
S10b: <i>Equisetum fluviatile</i> swamp (<i>Carex rostrata</i> subcommunity)	<i>Equisetum fluviatile</i>	<i>Carex rostrata</i> , <i>Menyanthes trifoliata</i> , <i>Potentilla palustris</i> , <i>Galium palustre</i>	Up to >100 cm	Sediment pH 5.2 to 6.4; eutrophic to oligotrophic conditions	Silty, sandy or peaty
M5: <i>Carex rostrata</i> – <i>Sphagnum squarrosum</i> mire	<i>Carex rostrata</i> , <i>C. nigra</i> , <i>Eriophorum angustifolium</i> , <i>Potentilla palustris</i> , <i>Aulacomnium palustre</i> , <i>Sphagnum squarrosum</i>	<i>Menyanthes trifoliata</i> , various small herbs, <i>Sphagnum recurvum</i> , <i>S. palustre</i> and 'brown' mosses (<i>Calliergonella cuspidata</i> , <i>Calliergon stramineum</i>)	?	pH ca. 4; dissolved Ca 5 to 15 mg/l; mildly acidic, oligotrophic conditions	Usually on peat

¹⁶ See: www.eunis.eea.eu.int/habitats-factsheet.jsp?idHabitat=5256

¹⁷ Data derived from Rodwell (1991-2000) and Wheeler et al (2003)

Community	Constant species	Frequent species	Water depth range	Water chemistry	Substrate
M9: <i>Carex rostrata</i> – <i>Calliergon</i> moss mire	<i>Carex rostrata</i> , <i>Eriophorum angustifolium</i> , <i>Galium palustre</i> , <i>Menyanthes trifoliata</i> , <i>Potentilla palustris</i> , <i>Calliergonella cuspidate</i>	Many, including <i>Carex diandra</i> , <i>Equisetum fluviatile</i> and mosses such as <i>Campylium stellatum</i> & <i>Calliergon giganteum</i>	-40 to +10 cm but never dessicated for long periods (Rodwell, 1991)	pH (>5) >6; dissolved Ca 15 to 50 mg/l; oligotrophic base-rich conditions	Usually on peat
S27a: <i>Carex rostrata</i> – <i>Potentilla palustris</i> tall-herb fen (<i>Carex rostrata</i> – <i>Equisetum fluviatile</i> subcommunity)	<i>Carex rostrata</i> , <i>Galium palustre</i> , <i>Menyanthes trifoliata</i> , <i>Potentilla palustris</i> , <i>Equisetum fluviatile</i>	<i>Cardamine pratensis</i> , <i>Agrostis stolonifera</i>	-40 to +10 cm	pH 5.0 to 7.0; dissolved Ca 10 to 90 mg/l; oligotrophic conditions	Usually on peat

5.10 The Okefenokee Swamp, Everglades and Florida lakes: floating wetlands in southern USA

In two of the USA's great wetlands – the Okefenokee Swamp in South Georgia and the Florida Everglades – floating peat masses form important habitat features. These are known by distinct local names referring to their various stages of development. The Okefenokee derives its name from the Native American phrase “land of the trembling earth”, reflecting the abundance of buoyant peat mats.

In these wetlands, peat blocks become buoyant and detach themselves from the bottom of waterbodies due to the build-up of methane. Binding of the bottom sediment by the rootstocks of aquatic lilies and arrowhead probably assists the formation of ‘chunks’ of peat (Sklar & van der Valk, 2003; Lodge, 2004); a very similar process has been described for uplifting peat masses in the Okavango Delta of Botswana (Cowling et al, 1997). This detachment and flotation is known as a ‘blow-up’ in Okefenokee (**Figures 4 and 12**), and disturbance of the bottom by alligators and snapper turtles may contribute to the occurrence of such events (Edwards, 2003). Loose peat and detritus may also aggregate along shorelines to form a substrate suitable for colonisation by wetland vegetation (Cypert, 1972) or ramifying root masses of raft-forming plants may grow outwards from the water margin.

In the Everglades, buoyant peat masses are called ‘pop-up islands’ (eg Sklars & van der Valk, 2003; Brandt et al, 2006); in Okefenokee they are known as ‘batteries’ (Cypert, 1972). In the Loxahatchee National Wildlife Refuge there are around 4,000 such pop-ups according to Lodge (2004). These can have a surface level up to 1 m above the water line (Lodge, 2004; Brandt et al, 2006) and become colonised by woody plants such as wax myrtle and swamp bay, the margins fringed by *Cladium* and wetland ferns. In the acidic waters of Okefenokee, early colonists of the exposed peat include *Andropogon glomeratus* (broom sedge), *Carex* spp and *Rhynchospora* spp (Edwards, 2003); *R. inundata* can be a dominant pioneer species on vegetating batteries, as has also been noted on emerging peat masses in New England ponds (Craine, 2003). Subsequent succession involves colonisation by woody plants.

In both Okefenokee and the Everglades, batteries/pop-ups may develop into peat islands which become anchored to the bottom by the weight of woody plants, and penetrated by tree roots (Lodge, 2004; Edwards, 2003). The wooded islands are known as ‘houses’ in Okefenokee (Cypert, 1972) and the climax vegetation is an ombrotrophic “cypress dome” (Barbour & Billings, 2000). In the Everglades, floating peat masses represent one of several types of ‘tree island’ (Sklar & van der Valk, 2003). Stratigraphic studies indicate that tree islands in the Everglades have formed within the past 1,300 years, and are thus relatively young features in relation to the development of the Everglades system.

Floating rafts or islands of vegetation occur commonly on Florida lakes, where they are known as ‘tussocks’. These can be divided into ‘mud tussocks’, in which large amounts of organic matter are held amongst the root mat, and ‘floating-type tussocks’ with little or no organic matter (these also tend to be dominated by smaller plants) (Mallison et al, 2001). The floating islands of the Orange Lake system have been characterised by Mallison et al (2001) as:

- Islands dominated by *Oxycaryum cubense* and *Hydrocotyle ranunculoides*, characterised by lateral outgrowth of floating stems into open water. These are relatively thin rafts with a mean thickness of 24 cm
- Islands dominated by the grasses *Panicum hemitomum* and *Sacciolepis striata*
- *Typha*-dominated formations with *Bidens* and *Polygonum* spp
- Stands dominated by *Pontederia cordata* (pickerelweed), a semi-aquatic plant with a thick creeping rhizome. *Pontederia* islands have thicker mats (mean thickness 50 cm)

The floating-leaved umbellifer *H. ranunculoides* was a significant component of almost all Orange Lake floating islands.

5.11 The *flotant* of the Mississippi delta

Floating vegetation rafts, known locally as *flotant*, form an extensive part of coastal fresh- and brackish- water wetlands in the Mississippi delta, Louisiana (Russell, 1942; Swarzenski et al, 1991; Sasser et al, 1996). Indeed, the Mississippi Delta Plain supports one of the major concentrations of floating wetlands worldwide (Swarzenski et al, 1991). Although there has been a considerable decline in the area of ‘thick-mat’ flotant in recent decades, >350,000 acres (141,643 ha) existed in the Barataria and Terrebonne basins in 1990 (Sasser et al, 2007).

The most extensive form of ‘thick-mat’ *flotant* in freshwater habitats is dominated by maidencane (*Panicum hemitomum*), a tall wetland grass with a dense fibrous root system. Minor components of these mats include the ferns *Thelypteris palustris* and *Osmunda regalis*, various vines and small quantities of cut-grasses (*Leersia* spp.) and *Sagittaria latifolia*. *Panicum* thick-mat floats throughout the year, its movements tracking ambient water levels. This is the most buoyant form of flotant, characterised by high fibric content in the uppermost 30 cm of the mat, low bulk-density and very low mineral content (Swarzenski et al, 1991). The very dense upper layer 20-30 cm deep consists of intertwined live and dead roots binding decaying root matter; below this a peat zone develops at 30-50 cm, penetrated by a few live roots. The underlying lens of free water varies seasonally but is typically about 50 - 80 cm deep, though the mat may rest on the bottom during drought conditions. In some cases, the marsh mat overlies “fluid organic ooze” rather than clear water (Sasser et al, 1996).

It has been suggested that maidencane thick-mat flotant results from vegetation development over buoyant but land-bound peat which eventually floats free from the underlying substrate. It appears unlikely that it develops from encroachment of open water from the edges. By contrast,

Russell (1942) concluded that flotant had increased greatly during the early 20th century as a secondary community developing over masses of introduced *Eichhornia* (water hyacinth) and *Alternanthera philoxeroides* (aligatorweed) – although he recognised that there were also stands of ‘ancient’ flotant.

In waters of intermediate salinity, *Sagittaria lancifolia* (= *S. falcata*) floating mats show more restricted, seasonal buoyancy (Swarzenski et al, 1991). These are dominated by *S. lancifolia* with some *Eleocharis* spp, *Panicum*, *Spartina patens* and patches of *Typha latifolia*. In the Jean Lafitte National Historical Park this vegetation has been described as dominated by *S. lancifolia*, *Typha* spp, *Schoenoplectus americanus* and *Spartina* spp (Nolfo-Clements, 2006). These arrowhead mats are loose and soft because *Sagittaria* does not form an extensive fibrous root system. In autumn the vegetation dies back and the raft subsides into the water (Sasser et al, 1996).

In spike-rush ‘thin-mat’ marshes a short, dense sward of *Eleocharis baldwinii* binds the upper layer of mats which are no more than 30 cm deep including the detritus layer (Sasser et al, 1996). The mat is suspended over watery peat and clay layers to a depth of c130 cm depending on seasonal water levels. Thin mats may be submerged in winter and thin-mat marsh may be associated with a degradation of thick-mat marsh in a reverse succession back to open water. Thin-mat marsh may be a secondary formation resulting from the gaseous upwelling of decaying organic material on the lake bed, which rises to the surface and becomes colonised by seedlings.

In brackish conditions *Spartina patens* thin-mat flotant fluctuates only slightly in response to changes in water level and is characterised by its low fibric content and 50% by weight mineral sediment content (Swarzenski et al, 1991). This was classified by Sasser et al (1996) as non-floating quaking marsh.

Battaglia et al (2007) have documented the development of wax myrtle (*Morella cerifera*) scrub on unburned thick-mat flotant. This development of a woody overstorey enhances structural complexity and species diversity but the longevity of the wooded phase is unknown. Shrub cover has increased on some coastal flotant systems since the 1950s, probably as a result of policies to avoid fires in protected wetlands. As thickets of *Morella* mature, shade-tolerant ferns (including *Thelypteris palustris*) and *Sphagna* increase. However, the weight of woody shrubs causes the formation of small holes in the floating mat. These pools are colonised by aquatic plants and amphibian larvae benefit from their isolation from predatory fish; invasion by emergent swamp plants probably indicates a process of re-consolidation of the floating mat. The authors observe that this “perforated mat condition may be a phase of flotant dynamics”.

It is important to note that *flotant* formation results from a combination of hydrological and other factors rather than the presence of specific plant communities per se. Thus flotant is very largely restricted to the Mississippi Delta Plain and is rare or absent in other coastal wetland systems on the Gulf of Mexico. The Chenier Plain borders the Mississippi Delta to the west and supports similar wetland plant communities in terms of species composition but floating mats are rare; for example, 95% of maidencane marsh in the Mississippi Delta Plain is buoyant but almost all stands on the Chenier Plain are attached (Visser et al, 2000). This may reflect the predominance of mineral sediments over organic soils on the Chenier Plain as well as hydrological differences.

5.12 Floating wetlands in Central and South America

Van Duzer (2001) describes 15 rafts of *Cladium californicum* which float on the surface of the Zacaton *cenote* (karstic sinkhole) in northeastern Mexico (**Figure 13**). These mobile islands are

3 to 10 m in diameter, 1 to 1.5 m thick and are apparently formed from buoyant aggregations of tufa, the *cenote* having vertical cliffs with no marginal vegetation.

Floating wetlands feature in several aquatic ecosystems in South America. Three distinct types of *embalsado* (soil-retaining floating raft) have been identified in an inventory of biotopes, along with Amazonian floating islands and two types of 'floating meadow' or *camalotale* (mostly soil-less floating rafts) (ITE/IRSNB, 1996).

Embalsados of the Chaco region (the Río de la Plata basin straddling the borders of Bolivia, Paraguay and Argentina) are dominated by tall graminoids along with wetland herbs, climbers and even small trees. *Cyperus* – *Fuirena* *embalsados* are dominated by *C. giganteus*, *F. robusta*, *Oxycaryum cubense*, *Schoenoplectus lacustris* ssp *validus* and *Cephalanthus glabratus* with a wide range of associates. This is the characteristic floating raft vegetation of the great esteros and lagoons of the Chaco. *Typha* rafts, by contrast, are dominated by *T. domingensis* with *T. latifolia*, *F. robusta*, *Baccharis salicifolia*, *Eleocharis acutangula* and *Ceratopteris pteridoides*.

In the Lagunas and Esteros del Iberá Ramsar Site in Corrientes province, Argentina, floating *embalsados* cover the shorelines of the oligotrophic lake complex. These are dominated by *C. giganteus* and *F. robusta* with associated *Panicum*, *Talia* and *Zizania* spp. They provide refuge and habitat for many of the vertebrates characteristic of the system and play an important hydrological role¹⁸. The nutrient dynamics of these *embalsados* have been studied by Gantes et al (2005).

Embalsados extend into the deltaic reaches of the Paraná River, where floating mats of *C. giganteus* rise and fall with changes in water level and remain isolated from sediment inputs (Pratolongo et al, 2007). Buoyant mats extend into areas with a tidal amplitude of around 1 m, though conditions are fresh due to discharge from the river. These swamps cover >400 km of the delta, although this figure includes both rooted and floating stands (**Figure 14**).

The Pantanal basin is located in the Mato Grosso, the upper part of the Rio Paraguay system close to the border between Brazil and Bolivia. Vegetation rafts known as *baceiro* or *batume* form on seasonally inundated floodplains and can cover hundreds of square kilometres during high-water periods (ITE/IRSNB, 1996). In long-lasting floating mats, succession begins with aggregations of free-floating macrophytes (*Salvinia*, *Pistia*, *Eichhornia*) followed by an *Oxycaryum cubense* floating sedge raft stage. Ferns (including *Thelypteris interrupta*) and the shrub *Ludwigia nervosa* may follow (Pott & Pott, 2004). These *batume* cover around 2.4% of the entire Pantanal and provide important habitat for species such as Yacaré Caiman and Marsh Deer (Da Silva et al, 2000).

In central Amazonia, floating rafts or *matupas* are formed by soil-retaining mixtures of *Paspalum repens*, *Echinochloa polystachya*, *Oryza perennis*, *Leersia hexandra* and several other species, supported by free-floating aquatics (*Pistia*, *Eichhornia*, *Salvinia*), and hosting climbers and even occasional terrestrial shrubs and trees (ITE/IRSNB, 1996). In the Manaus region of Brazil, the succession is from mats of free-floating *Eichhornia crassipes* and *Salvinia auriculata* to a secondary community of grasses and sedges which may be colonised subsequently by climbers and *Montrichardia arborescens*, a tree-like member of the arum family. In this region, the Lago dos Patos is described as having a floating mat 200 m wide, 3 km long and more than 4 m thick¹⁹.

¹⁸ Ramsar Information Sheet, accessed at: http://www.ramsar.org/ris/ris_argentina_ibera_e.htm

¹⁹ Smithsonian National Museum of Natural History, Centres of Plant Diversity website: <http://www.nmnh.si.edu/botany/projects/cpd/sa/sa5.htm>

Soil-free floating rafts (*camalotales*) of the rivers and floodplains of the Paraná basin are dominated by the floating grass *Panicum elephantipes*, other aquatic grasses, pontederiads (water-hyacinth relatives) and free-floating aquatics (ITE/IRSNB, 1996). On the Orinocco river system in Venezuela, floating rafts are composed of *Eichhornia crassipes*, *Paspalum repens*²⁰, *Pistia stratiotes* and *Salvinia* spp (ITE/IRSNB, 1996: 'Orinocco floating grasslands').

On the Pacific coast of Costa Rica, the Laguna Sierpe is a shallow lake fringed by floating-mat vegetation (Haberyan et al, 2003) though the precise composition or structure of this does not appear to be documented.

In the arid tundra-desert of the Andean Altiplano in northern Chile, peatland *bofedales* occur in valley bottoms. The Rio de la Gallina peatland is a narrow, linear 3 km long mire surrounding a stream channel. Earle et al (2003) describe how vegetation dominated by the rushes *Oxychloe andina* and *Patosia clandestina* has formed a peat-accumulating raft perched over a lens of around 80 cm of free water. Very rapid peat accumulation (and thus carbon-sequestration) occurs in this habitat, exceeding data for Northern Hemisphere *Sphagnum* peatlands. This is probably due to the very cold, arid and hypoxic climatic conditions. Current *Oxychloe* peat mats have developed during the past 50 years, floating mat formation being associated with a shift to a low-energy, ponded stream system.

5.13 Floating wetlands in Africa

Papyrus and *Miscanthidium violaceum* are bulky tropical cyperaceae which can be dominant in swamp vegetation which is either rooted or forms a floating raft. Papyrus is of course well-known as the material used for parchment-making by the ancient Egyptians; more recently, both plants have been trialled for use in the biological treatment of wastewater in Uganda, with papyrus showing promising results (Kyambadde et al, 2004).

Papyrus and *Miscanthidium* grow in extensive swamps around the fringes of Lake Victoria in East Africa with some *Phragmites mauritianus*, *Typha domingensis* and other tall swamp species (Kansiime, Saunders & Loisele, 2007). Rich in air vacuoles, the root masses of papyrus form floating rafts which extend from the lake edge out over open water up to 10 m deep (Azza et al, 2000 and references therein). Kansiime, Saunders & Loisele (2007) record that "Papyrus dominated wetland systems often form a buoyant floating mat due to the interlocking nature of the rhizome and root systems. The papyrus mat forms a floating structure strong enough to support the weight of a man, and consists of interstitial spaces through which water passes (providing the plants with a nutrient source)." *Miscanthidium* can also occur as a floating mat, its interlacing root structure trapping large volumes of detritus: "One can walk on this mat without realising that there is a water column beneath, as deep as 2.5 m." In the Lake Victoria wetlands, this root mat may vary from 0.5 m thick in papyrus rafts to 1.8 m thick in *Miscanthidium*.

In the Namanve Swamp on the northern shore of Lake Victoria, Eggeling (1935) described how uprooted mats of lake-edge papyrus swamp would float and re-anchor themselves amongst shoreline vegetation. However, the true floating mat vegetation at this site comprised a 20 m wide 'fern and sedge community' consisting of smaller plants such as the fern *Thelypteris striata*²¹, *Pycerus* spp, dwarf papyrus *Cyperus haspan*, the cut-grass *Leersia hexandra*, umbrella-sedges *Fuirena* spp and *Polygonum* spp, "their roots so bound together as to form a thin, compact, floating mat of vegetation". He described how, when walked upon, "...this mat sways and sags in a horrible manner beneath one's feet, several square feet at a time disappearing below water should one cease moving even for a moment". Similar occurrences are reported from Lake Kyoga (**Figure 15**).

²⁰ *P. fasciculatum* according to ITE/IRSNB (1996)

²¹ '*Cyclosurus interruptus* var. *striata*'

Elsewhere in Uganda, Denny (1973) documented the extensive floating swamps of Lake Bunyonyi, an upland site where conditions were suboptimal for papyrus. Here, *Cladium jamaicense* was dominant, accompanied by small amounts of papyrus and an understory of the fern *Thelypteris confluens* [= *squamigera*]. At Lake Bunyonyi, rhizomatous mats of *C. jamaicense* extend out onto the water surface in sheltered bays and inlets. Occasionally, outer portions become detached and form free-floating islands, which may drift and accumulate in windward bays.

The Sudd wetlands of southern Sudan are one of the largest tropical wetlands in the world, covering 57,000 km² around the upper reaches of the Bahr el Jebel/White Nile. Swamps are variously dominated by papyrus, *Vossia cuspidata* or *Typha domingensis*, including extensive areas of floating vegetation. The Dinka, Nuer and Shilluck peoples depend on the wetlands, which are of international importance for wintering water birds (BirdLife International, 2007).

In the Okavango Delta of Botswana, floating sudds cover “many hundreds of square kilometres” (Cowling et al, 1997). Ellery et al (1990) described two alternative pathways:

- ‘Floating organic sudds’ result from gaseous uplifting of submerged organic-rich substrates, which once exposed are colonised by local wetland plants. Rates of spread are slow.
- ‘Plant sudds’ are formed by the vegetative spread of the sudd-forming sedge *Pycnus nitidus*, which requires physical support from loose detrital material in the water column or submerged masses of the fine-leaved aquatic club-rush *Websteria* [= *Scirpus*] *confervoides*. These rafts expand rapidly.

Eventual succession is to floating swamps dominated by papyrus in the upper delta or *Miscanthus junceus* in the middle reaches. Papyrus mats can extend 15-20 m out over deep water; they can be so bulky as to become grounded, blocking channels and influencing the morphology of the delta (Hughes & Hughes, 1992).

Floating papyrus swamps also occur very extensively in the Zambezi Delta in Mozambique, where the total area of papyrus is around 84,000 ha including >50,000 ha within the Cuacua floodplain (Beilfuss et al, 2001). These rafts are colonised by shallow-rooted wetland plants such as *Echinochloa scabra*, *Ipomea aquatica*, *Pycnus nitidus* and *Vossia cuspidata*.

In Lake Kariba on the Zimbabwe/Zambia border, prolific floating mats of the alien aquatic fern *Salvinia* were colonised by the reed *Phragmites mauritianus* and *Althernanthera nodiflora* (Boughey, 1963, cited by Van Duzer, 2004). On Volta Lake, a large reservoir in Ghana, sudd mats of *Vossia cuspidata*, *Leersia hexandra* and *Oryza borthii* became established around drowned trees; elsewhere in the lake, aggregations of *Pistia stratiotes* became colonised by *Typha domingensis* and *Oxycaryum cubense* (Petr, 2000).

5.14 Floating wetlands in Asia

Loktak Lake covers 289 km² in Manipur, India, and is characterised by the abundance of floating vegetation rafts known as *phoomdis* or *phumdis* (**Figure 16**). Loktak is a major ecological and socio-economic resource, supporting a population of around 10,000 people through the provision of hydropower, irrigation, fisheries, aquaculture and use of wild plants (WWF India, 2006).

The Keibul Lamjao National Park, in the southern part of the lake, is a unique floating wildlife reserve and the sole habitat of the endangered Manipur Brow-antlered Deer or *Sangai*. The National Park supports the largest concentration of phumdis, covering 40.5 km² (Sanjit et al, 2005). These range from a few centimeters to 2 m in thickness and are characterised by black,

humic soil (Singsit, 2003). Phumdis are heterogeneous masses of soil, vegetation and organic matter, often dominated by the reed *Phragmites karka* but other important species can include *Eichhornia crassipes*, *Oryza sativa*, *Zizania latifolia*, *Cynodon* spp, *Sagitaria* spp, *Saccharum latifolium*, *Leersia hexandra* and *Carex* spp (Sanjit et al, 2005). Sixty plant species are widespread and common on phumdis (Trisal & Manihar, 2004).

Elsewhere in Asia, Petr (2000) refers to the occurrence of several square kilometers of thick floating mats on Bung Borapet reservoir in Thailand. These are “very resistant to wind and wave action” and are composed of *Coix aquaticus*, *Isachne globosa* and *Leersia hexandra*.

In Japan, Mizorogaike Pond north of Tokyo City is a warm-temperate waterbody partly covered by a floating but loose, unconsolidated peat mat. The mat surface is dominated by *Menyanthes trifoliata* with occasional associates including *Eriocaulon* spp (pipeworts), *Rhynchospora fauriei*, *Carex thunbergii* and *Phragmites australis*. Rising from the surface are hummocks of vegetation including *Sphagnum palustre* and various woody species. As the peat accumulates above the surface and flooding is decreased, the successional sequence is *Menyanthes* → *Rhynchospora fauriei* → *Eriocaulon sikokianum* → *Sphagnum cuspidatum* (Haraguchi, 1991b).

The raft undergoes an annual cycle of emergence and submergence, rising in July to December, when it may float over 20-100 cm of free water. The floating raft of Mizorogaike Pond has been much-studied (Haraguchi & Matsui, 1990; Haraguchi, 1991a, 1991b and references therein; Haraguchi, 1996; references indexed by Van Duzer, 2004, p 388). As in floating mires elsewhere, *Sphagnum* dominance results in biotic acidification and low pH whilst segments of the raft which remain in contact with surface water have higher pH (Haraguchi & Matsui, 1990).

5.15 Floating wetlands in Australasia

Millington (1954) described the formation of scraw mires in flushes alongside valley streams in the New England Plateau of New South Wales, Australia. This is a seral stage in the succession: aquatic vegetation → reedswamp → sedge swamp → *Restio gracilis* (cord rush) ‘scraw’ → *Sphagnum* bog. He also describes quaking bogs in which peat masses are bound by the rhizomes of *Carex gaudichaudiana*, *Calorophus minor* and *Restio gracilis*. As hummocks develop above the scraw surface, they can eventually sink into the peat, and the heath shrubs growing atop the hummocks drown. *Sphagnum* communities are very localised in Australia and Whinham et al (2003) do not refer to any floating formations. The Floating Islands Lagoon at Pirron Yallock, Victoria (Australia) contains several visibly mobile peat masses supporting large trees (**Figure 17**).

In New Guinea, floating peat rafts occur as part of the hydrosere in lakes associated with volcanic or tectonic landforms. Whinham & Hope (2005) describe Nurank Swamp, a landslide basin in the Papua New Guinea uplands. Here a 1 m deep peat mat floats on a lens of water overlying deep lake bed sediments.

The forester Charles Lane-Poole (undated) described floating rafts of vegetation on the Embi lakes, Papua New Guinea. He recorded the dominant water-margin plant as ‘*Sisum antheminticum*’²², which forms a dense mass of horizontal stems extending 5 or 6 m out into open water. This provides a platform for other species such as ‘*Limmonthemum indicum*’²³, the fern *Thelypteris interrupta* and a *Cyperus* species whose masses of ramifying roots provide buoyancy for the raft. Petr (2000) mentions the formation of *sudd* mats in Sirinumu Reservoir, Papua New Guinea, but does not specify the type of vegetation.

²² Although Lane-Poole refers to ‘*Sisum*’ as a ‘lily’, he might be referring to *Sium* sp., a genus of wetland umbellifers (Apiaceae)

²³ Presumably referring to *Limnanthemum indicum*, now known as *Nymphoides indica*, a member of the bogbean family (Menyanthaceae)

Haberle et al (2006) briefly describe a littoral floating vegetation mat at Lake Euramoo, a volcanic crater lake in tropical north-east Queensland, Australia. This comprises water-dropworts (*Oenanthe* spp) and the pan-tropical wetland fern *Dryopteris gongyloides* (*Thelypteris interrupta*) with some '*Eleocharis equisetum*'²⁴. This mat forms part of a marginal zone up to 30 m wide and palynological evidence suggests that it has been a persistent feature for several centuries.

Floating grass mats comprising *Leersia hexandra*, *Hymenachne acutigluma*, *Urochloa mutica* and *Ludwigia ascendens* occur along the margins of billabongs (oxbows) in the Kakadu Region of northern Australia (Finlayson et al, 2006). Hill et al (1987) provide a more detailed description of the vegetation and fauna of floating mats on billabongs on the Finnis River floodplain in the Northern Territories. These extend up to 65 m from the shore and showed a distinct zonation of plant assemblages. Near the bank, tall rooted emergents such as *Phragmites karka* and *Typha orientalis* grow through the mat; floating vegetation further out is dominated first by the sedge *Hymenochaeta grossa* and the fern *Thelypteris interrupta* then the grasses *Isachne globosa* and *L. hexandra*. At the outer edge of the mat there is sparse cover of floating grasses over aggregations of free-floating macrophytes such as *Pistia stratiotes*. The mat vegetation is low in stature but the substrate of living and dead plant material can reach 1.3 m thickness. The raft is suspended over free water up to 3 m deep.

Hill et al interpret the development of these floating mats as follows. Masses of free-floating *Pistia* plants aggregate against sheltered banks and are colonised by trailing stoloniferous grasses such as *L. hexandra* and *I. globosa* which spread from the water margin. These bind the *Pistia* masses to the shore like a net, then grass cover and accumulation of organic matter increase within the young mat. This provides a substrate for less aquatic plants like *T. interrupta*, the sedge *Cyperus paltystilis* and various vines which further consolidate the raft. Buoyancy is attributed to air spaces in the root mass, accumulation of low-density organic matter and trapped gases from decomposition.

The Lagoon of Islands, a lake covering 9.17 km² in the Central Plateau of Tasmania, formerly supported extensive areas of floating-mat swamp. These were characterised by a raft of the sedges *Baumea arthrophylla* and *Chorisandra australis* "whose interlacing rhizomes form a network firm enough to allow a man's cautious passage" (Tyler, 1976). These mats overlay 2 m of peaty water above a firm peat substrate. The surface of the mat lay partially submerged but was dotted with hummocks formed by *Carex appressa* which grew up above water level. These tussocks were colonised by herbaceous plants such as *Restio tetraphyllus* and eventually by woody shrubs including the Tasmanian endemic *Callistemon viridiflorus*. A few islands even supported eucalypts but the weight of these islands eventually caused a moat of water to form around them as they subsided, followed by sinkage into a pool. These pools, containing the woody remains of drowned plants, were presumed to be recolonised by the spreading rhizomes of *Baumea*. Tyler (1976) claimed that "there is no other system based on this type of vegetation", although the perforated flotant invaded by wax-myrtle in coastal Louisiana (Battaglia et al, 2007) is clearly analogous.

After damming of the lake in 1964, changes in water level led to the decline and break-up of the raft, which had disintegrated by 1987-88. Water quality in the lake subsequently declined, resulting in hypertrophic conditions and algal blooms. Attempts to restore a macrophyte-dominated system have seen the recolonisation of *B. arthrophylla* since 1998, apparently at an accelerating rate (Maxwell & Tyler, 2006). However, the sedge has appeared not only around

²⁴ This presumably means *Eleocharis* (spike-rush) and *Equisetum* (horsetail) species since there is no such plant as *Eleocharis equisetum*

the rim of the lake but also in deeper central areas, suggesting that mat formation in this system may not be simply through centripetal expansion from the lake margins.

5.16 Floating wetlands on tropical islands

In the Kawai Nui wetland on Hawaii, an extensive floating vegetation mat has developed over water up to 3 m deep and is dominated by the non-native California grass (*Brachiaria mutica*), although indigenous wetland plants also occur in the mat (Kailua Bay Advisory Council, 2002). Associated species include *Commelina diffusa*, *Sagittaria latifolia* and occasional *Typha latifolia*.

Lake Tagimaucia, a freshwater crater lagoon in Fiji, is mostly covered by a floating, peat-accumulating mat of the sedge *Lepironia articulata* and algae (Southern et al, 1986). The three volcanic crater lakes of Easter Island have extensive floating wetlands, 80% of the 100 ha Rano Kuiu being covered by peat-accumulating mats of *Scirpus californicus* and the endemic moss *Campylopus turficola*; floating mats of the latter also cover parts of Rano Raraku (Schlatter, 1993).

6 THE DEVELOPMENT, LONGEVITY AND SUCCESSIONAL FATE OF FLOATING WETLANDS

Successional change in schwingmoor-type mires has often been studied because they provide excellent conditions for stratigraphic and palaeoecological studies, with sediments and biological remains well-preserved in and below the floating raft of peat. The formation of floating rafts of vegetation is commonly demonstrated to be a key stage in the formation of terrestrial peatlands in post-glacial basins, in both boreal and temperate zones of the northern hemisphere (eg Tallis, 1973; Foster & Key, 1984; French & Moore, 1986; Swineheart & Parker, 2000; Anderson et al, 2003). Some such mires can be quite transitory stages in the terrestrialisation of lake basins but others can apparently be very long-lived features.

Floating mires are sometimes perceived to be remnants of undisturbed wilderness. The great American naturalist and philosopher Henry Thoreau was entranced by Gowing's Swamp (now known as Thoreau's Bog), a small kettle-hole schwingmoor near Concord, Massachusetts. He believed the bog to be one of the undisturbed relict habitats in New England, which remained "as purely primitive as they were a thousand years ago, which have escaped the plow, the axe, the scythe and the cranberry rake, little oases of wilderness in the desert of our civilization" (cited by Hemond, 1980). In fact, Hemond (1980) used the lead isotope ^{210}Pb to estimate the net rate of peat accumulation in Thoreau's Bog and concluded that the floating mire only formed about 500 years ago and was therefore "not a relict of colder, early postglacial periods" despite the presence of plants normally found further north.

Some evidence does suggest that schwingmoor-type mires can be very long-lived and may therefore support relict plant or invertebrate communities. Paynological data reportedly suggests that the floating mire at Ponemah Bog in New Hampshire started to form 4,000 to 6,000 years ago²⁵. The inter-dunal schwingmoor at Vankervelsvlei in the Western Cape (South Africa) is reported to have formed around 30,000 years ago (Irving & Meadows, 1997), although there appears to be little information on its current structure.

Basin morphometry and climate are likely to be primary determinants of the speed and direction of successional development in lakes, with succession to raised bog requiring plentiful rainfall and high humidity (Wetzel, 1983). Schwingmoor formations are often associated with steep-sided basins, usually kettle-holes, though they can also occur in inter-dunal depressions (Irving & Meadows, 1997) and in oxbows (Nagy et al, 2007). Wetzel (1983) and Wilcox & Simonin (1988) associate the development of schwingmoor with relatively deep lake basins of small surface area: in such situations, floating or semi-floating littoral vegetation encroaches from the periphery of the lake towards the centre long before the basin fills vertically with peat or other sediment. The oldest portions of the mat, nearest the shoreline, are attached to the underlying peat and represent the late stages of succession, typically with the development of bog woodland.

However, Bunting & Warner (1998) associate schwingmoor formation with relatively shallow lakes – and they point out that there is no clear explanation why some remain open waterbodies whilst others develop floating mats of vegetation. They postulate that factors could include whether a shallow lip to the basin provides purchase for mat-forming species, the nutrient status of inflowing waters and basin morphology (mat growth may have limits over deeper water). Therefore schwingmoor development "may be stochastic, or linked to the presence of some morphological feature". Warner et al (1989) hypothesise that, in southern Ontario, forest clearance resulted in increased run-off, especially during spring snow-melt. Water levels rose in kettle-holes, either as a result of spring flooding or increases in local groundwater levels. Rising water levels may have suppressed established marginal vegetation and favoured pioneer raft-

²⁵ See www.nhaidubon.org/sanctuaries/ponemah

forming species such as *Chamaedaphne calyculata*, *Potentilla palustris* and *Decodon verticillatus*. The precise causal mechanisms are uncertain but the authors are confident that floating mires in their study area “are largely man-made ecosystems about 150 years old”. They suggest that, “The floating mires in Ontario demonstrate that human land-use activities are a widespread feature of floating mire formation”.

The direction of successional change is not always straightforward and probably varies considerably from site to site. At Wybunbury Moss, Cheshire, mire communities “do not bear a seral relationship to one another, but...their distribution can be explained in terms of substratum water chemistry and hydrological factors” (Green & Pearson, 1977). External influences can have marked, but not necessarily irreversible, effects: at Wybunbury, a brief phase of tree colonisation was associated with drainage works in the late 19th century but ended when drains became defunct; short spurts of renewed tree growth were probably associated with efforts to drain neighbouring land during the two World Wars (Green & Pearson, 1977).

The drowning of trees under their own weight once they reach a certain size apparently inhibits tree colonisation at Wybunbury Moss (Green & Pearson, 1968), as it does at Chartley Moss in Staffordshire (Nature Conservancy Council, 1987). The sinkage of hummocks supporting shrubs has also been described from quaking ‘scraw’ bogs in New South Wales, Australia (Millington, 1954), from floating *Baumea* sedge mats in the Lagoon of Islands in Tasmania (Tyler, 1976) and from thick-mat flotant colonised by shrubs in Louisiana (Sasser et al, 1996; Battaglia et al, 2007). In northern USA, factors inhibiting the development of tree cover over mires include high water levels, recurrent fires, summer frosts, a lack of seed sources and mat structures incapable of supporting the weight of trees (Eggers & Reed, 1997).

Nonetheless, eventual succession from open vegetation to some type of woodland has been documented in many types of floating wetland, ranging from the ‘houses’ of the Okefenokee Swamp to floating bogs in North American kettle-holes, English schwingmooren and Dutch kragge fens. At least in some cases, floating peat rafts have become grounded by the time mature woodland develops.

Palaeoenvironmental studies can provide useful insights into the genesis of floating wetlands. At Flaxmere in Cheshire, for example, palynological and stratigraphic evidence shows that a floating raft of *Sphagnum cuspidatum* was possibly buoyed up by the rhizomes of *Eriophorum angustifolium* and *Scheuchzeria palustris* over open water. This probably required shallow water conditions (<2 m) and a depletion of ionic content in waters entering the basin (Tallis, 1973). Bellamy et al (1965) inferred the following successional development from stratigraphic and paleoecological evidence in a post-glacial basin near Darlington (County Durham). Open water with reedswamp was succeeded by a floating carpet of bryophytes, especially *Paludella squarrosa*, *Calliergon giganteum* and *Camptothecium nitens*, “at least in part supported by a raft of *Potentilla palustris* and *Menyanthes trifoliata*”. As the influence of base-rich groundwater was reduced at the mat surface, base-tolerant *Sphagna* colonised followed by a ‘wet heath’ phase and eventually a birch-dominated transition mire with some swamp. Wetland succession was terminated when the basin was infilled by downwash of mineral soils, probably following the establishment of agriculture in the surrounding landscape.

French & Moore (1986) present a detailed account of schwingmoor formation at Llyn Mire, a small basin mire in central Wales, based on palynological and stratigraphic studies. Interestingly, they associate schwingmoor formation with agricultural land management in the catchment of the original Cors Llyn lake about 500-600 years ago. Cultivation of hemp (*Cannabis sativa*) for rope-making, probably in Tudor times, coincided with this process and may have introduced sediment and nutrients which facilitated the spread of a sedge raft. A rhizome mat of *Carex rostrata* initially developed over peat in very shallow water but only extended across the surface of the lake around the time that *Cannabis* pollen appeared in the profile. This

raft provided physical support for *Sphagna*, especially *Sphagnum recurvum*, and subsequent development facilitated colonisation of cranberry (*Vaccinium oxycoccus*) and ericaceous dwarf-shrubs over a 1 m thick vegetation layer “capable of supporting the weight of a man”.

Bunting et al (1998) and Warner et al (1989) have also related schwingmoor formation in kettle-hole lakes in southern Ontario to changes in catchment land-use following the arrival of European settlers c1830. They suggest that many such wetlands only exist as a result of such changes, rather than being relict communities surviving from the early Holocene.

A similar example is provided by the post-glacial history of McCormick Point Wetland in southern Ontario, described by Campbell et al (1997). The basin originated as a slightly alkaline kettle-hole lake 11,750 years ago. At around 5,200 years BP a floating fen mat formed around the edge. This began to expand rather suddenly towards the centre of the basin 600 years ago and after 1830 the *Carex* ‘brown’ moss raft was replaced by *Sphagnum*-dominated schwingmoor. The authors conclude that “external forcing factors initiated these hydroseral changes”, which occurred as phases of rapid change interspersed by long period of apparent equilibrium. In this case expansion of the floating sedge mat 600 years BP coincided with the Little Ice Age period of climatic cooling, though the connection is unclear. The switch to *Sphagnum*-dominated floating bog coincided with land clearance by European settlers around the lake and is attributed to hydrological changes though the precise causal factors remain uncertain.

Magyari et al (2001) also linked human agricultural activities to successional development in a small valley mire at Nagymohos in the Carpathian foothills of north-east Hungary. The basin originally supported open water but by around 6,200 BC a floating, peat-accumulating mat of *Typha latifolia* and *Thelypteris palustris* had replaced open water. Within 300 years, this developed into a floating *Carex* – *Sphagnum* mire; initially this took the form of a transitional *Carex lasiocarpa* fen before sudden encroachment of *Sphagnum palustre* resulted in the formation of a floating *Sphagnum* lawn.

Anderson et al (2003) studied the chronology of peatland development in three New England lake basins. Succession reflected the size and morphology of individual basins but floating or hovering ‘bog mats’ formed a stage in the terrestrialisation process, preceding the spread of shrubby vegetation over the infilled basin.

Swineheart & Parker (2000) examined the development of Indiana peatlands. They identified a common successional pathway in post-glacial lakes and ponds, beginning with colonisation by stoneworts and other aquatic macrophytes. This was followed by the arrival of lilies and *Brasenia schreberi* (water-shield, a lily-like floating leaved plant), then colonisation of open water by a floating fen mat dominated by calcicolous mosses of the family Amblystegiaceae (*Calliergon* spp, *Campylium*, *Drepanocladus aduncus*, *Scorpidium scorpioides*). Some floating fens became *Sphagnum*-dominated bogs but all eventually terrestrialised into lowland forests dominated by *Acer rubrum*.

Godwin & Vishnu-Mittre (1975) inferred a floating ‘scraw’ mire as forming a stage intermediate between *Cladium* fen and acidic raised bog in the vicinity of Whittlesey Mere in the Cambridgeshire fenland.

The formation of schwingmoor in an inter-dunal lake at Vankervelsvlei in the Western Cape (South Africa) is considered by Irving & Meadows (1997) to be “a remarkable and rare landform in the context of the southern hemisphere”. Organic sediments began to accumulate in the open lake <40,000 years BP and schwingmoor apparently covered the lake by around 30,000 years BP. The site is now dominated by a sedge mire although it is unclear from Irving & Meadows’ study whether any lens of free water remains below the schwingmoor. Nonetheless, if their

interpretation is correct, it suggests a remarkably persistent schwingmoor stage, perhaps attributable to climatic factors.

TABLE 6.1: Rates of lateral expansion in some floating wetlands

Site	Habitat	Rate of spread	Reference
Harvard Pond, Massachusetts (USA)	<i>Chamaedaphne/Sphagnum</i> raft on shallow dam pond	6-7 cm/yr ⁻¹	Swan & Gill (1970)
Thoreau's Bog, New Hampshire (USA)	Ombrotrophic, acidic <i>Sphagnum</i> -dominated floating bog	5 cm/yr ⁻¹	Hemond (1980)
Okovango Delta (Botswana)	Tropical <i>Pycreus nitidus</i> sudd	1.46 m/yr ⁻¹	Ellery et al (1990)

Relatively rapid occlusion of open waterbodies within floating mire systems has sometimes been reported. Describing the development of schwingmooren on Cheshire kettle-hole lakes, Tallis (1973) reported that residual areas of open water at Abbots Moss and Wybunbury Moss had diminished within a decade due to encroachment of the *Sphagnum* raft. At Scouts Wood in Delamere Forest, a pool 100 m wide and 2.5 m deep became overgrown with *Sphagnum* within 40 years. At Philbrick-Cricenti Bog in New Hampshire, a kettle hole formed c18,000 years BP still contained open water used for fishing 150 years ago; this has now been engulfed by expansion of a floating mat of *Sphagnum* and cranberries, representing continuing expansion of the peat-forming bog into the deeper parts of the basin (New Hampshire Natural Heritage Bureau, 2006). Loss of open water to spreading rafts may be viewed as a problem if it results in the disappearance of wildlife habitat or the loss of highly valued eco-hydrological features. Crushell et al (2006) suggest that minerotrophic 'soak' ponds are a unique feature of Irish bog systems. Within Clara Bog in central Ireland, an open waterbody known as Lough Roe is known to have existed for >6,000 years and originally expanded as the bog developed. In 1837 it covered 12,000 m² and had only slightly diminished by 1920; by 1978, however, only 100 m² of open water remained, surrounded by floating scragh with just 5 m² remaining in 1991. This rapid loss of open water to floating bog is attributed to human modification of the hydrology of Clara Bog. The authors recommend the removal of the floating mat to restore minerotrophic open water conditions.

7 KEYSTONE PLANT SPECIES IN RAFT FORMATION

In North American kettle-holes, swamp loosestrife (*Decodon verticillatus*) and leatherleaf (*Chamaedaphne calyculata*) - a low-growing, evergreen shrub - are often mentioned in the context of floating raft formation. In New England, *C. calyculata* is the pioneer species invading open water and establishing a raft which is subsequently colonised by sedges, *Sphagna* and shrubs: "Leatherleaf spreads by means of an adventitious root system that produces the stable framework for the floating mat on which sediment builds up and *Sphagnum* accumulates", whilst the arching stems of *Decodon* produce "a floating network of branches that traps organic sediments and supports leatherleaf at the leading horizontal edge of the spreading bog" (Salett, 2002). Andreas & Bryan (1990) also ascribe a pioneering role to *Decodon*, which they refer to as "the purchase, or forerunner, taxon" in the development of *Sphagnum*-dominated floating mires. Robichaud Collins & Anderson (1994) also described *C. calyculata* and *D. verticillatus* as primary raft-forming species in New Jersey mires.

At Harvard Pond, Massachusetts, *C. calyculata* spread over the surface of an artificial shallow lake from multiple points of origin associated with tree stumps; *D. verticillatus* is dominant at the margins of the raft and a floating fringe of *Sphagnum cuspidatum* may also provide flotation for *C. calyculata* as the mat extends. Since *C. calyculata* stems contain no vacuoles and are not self-supporting, "support for horizontally spreading stems seems to be provided by other plants growing in the water along the bog margin" (Swan & Gill, 1970).

Decodon verticillatus has a wide distribution in North America and has been described as the keystone species in the formation of floating vegetation mats in an Arkansas bald cypress (*Taxodium distichum*) swamp (Huffman & Lonard, 1983). Succession is from a pioneer stage dominated by *D. verticillatus* through phases in which other herbs and then shrubs colonise the mat, leading eventually to *Taxodium* swamp woodland.

Bogbean (*Menyanthes trifoliata*) is very commonly described as a mat-forming species and is a dominant or major component of floating mires in north-western Europe, the Pyrenees (Chouard & Prat cited in Dansereau & Segadas-Vianna, 1952; Muller, 2006), Alaska (Racine & Walters, 1994) and elsewhere. Haraguchi (1996) investigated rhizome growth in a floating raft dominated by *Menyanthes trifoliata* in Japan. In basin wetlands in eastern North America, floating *Menyanthes* rhizomes initially "build a rather loose and flexible network, very resilient under water level fluctuations and wind-induced wave movements" (Dansereau & Segadas-Vianna, 1952). Stoneworts and other algae infill spaces in the mat and this consolidation enables species such as *Potentilla palustris* and *Calla palustris* to colonise. Turesson (1916) identified *Menyanthes* as the primary raft-forming species in Mud Lake, Washington State.

Potentilla palustris is also a common component of floating fen mats in North America and Europe. It plays an important role in initiating succession in open water habitats by forming a floating mat; on encountering open water, it produces a distinctive growth form in which "intensively-branched ramets occasionally form a dense layer of interwoven stolons" (Macek & Lepš, 2007). At Mud Lake, *P. palustris* was considered to be a colonist of pioneer *Menyanthes* rafts, subsequently spreading out into open water at the leading edge of the raft (Turesson, 1916).

Potentilla palustris may have a significant role as a pioneer raft-former in Britain. Meade & Wheeler (2007) report that it established over both shallow pits and the edges of a fluctuating gravel pit lake at Hatfield Moors, South Yorkshire. In one experimental plot, *P. palustris* has been one of the few introduced species to survive. Here it has formed a vigorous floating raft, although this only appears to have taken place since water levels have stabilised. The authors observe that "*Potentilla palustris* is the only species to have formed a floating raft on which

others can become established, and may eventually develop into a 'transition mire', as a precursor to raised bog".

Medium-sized semi-aquatic sedges (*Carex* spp) with extensive rhizome systems are often described as pioneer raft-forming species in northern fens. *Carex rostrata* is probably a key species, at least in Britain, where it is dominant in four NVC communities associated with floating-mat formation (see Section 4.4 of this report). At Clara Bog in central Ireland, *C. rostrata* was the principal recoloniser of plots where the existing floating mat had been removed (Crushell et al, 2006). It was referred to as a primary raft-forming species in some Central Russian turbaries by Kutz (1926). *Carex utriculata*, a closely-related North American species, often forms floating mats at lake margins in Canada (Cooper et al, 2007). However, this may generally be a species of firmer ground than *C. rostrata*, at least in north-eastern USA where the latter seems to be more specifically confined to floating mats or quaking mires (Bigley & Hull, 2000).

Carex lasiocarpa may also be a principal raft-forming species. It is commonly mentioned as a dominant species of floating mats in North American wetlands (eg Bowles & Jones, 2006; Judziewicz, 2001). A *Carex lasiocarpa* - (*Carex rostrata*) - *Equisetum fluviatile* community characterises floating fen mats in the Great Lakes region of North America²⁶. In the circumneutral, oligotrophic waters of Rogers Lake, a glacial basin in Montana, a floating raft of *C. lasiocarpa* forms a zone of vegetation distinct from *C. utriculata* swamp rooted in the substratum (Greenlee & Jones, 2000) and it may thus represent an expansion of littoral sedge fen over open water.

Carex aquatilis is another tall sedge which may play a role in floating mat formation in boreal zones. Floating mires dominated by *Carex aquatilis* over a ground layer of *Sphagna* have been described from Ontario²⁷ and it forms a component of floating groundwater-discharge fens in Interior Alaska (Racine et al, 1994). It is unclear whether *C. aquatilis* acts as a primary raft-forming species but its very crowded rhizomes (1,000-2,000 shoots/m²) (Cooper et al, 2007) may be suitable for mat-formation.

Carex limosa is characteristic of mid-seral floating mat development in kettle-holes in northern USA, where it succeeds a *Menyanthes trifoliata* – *Carex utriculata* raft (Gage & Cooper, 2006b). In the Thompson Chain of lakes in Montana a floating *C. limosa* community has been described by Greenlee & Jones (2000); this also contains *C. interior*, *C. diandra*, *Eriophorum gracile* and *Scheuchzeria palustris*, a combination of species which suggest conditions transitional to bog. In the Rhodopes mountains of Bulgaria, *C. limosa* dominates some floating raft forms of *Carex rostrata* – *Sphagnum recurvum* poor-fen in which *Menyanthes* is also abundant (Mire Ecology Working Group, undated). Whilst *Carex limosa* is a common associate of species such as *Menyanthes*, *C. lasiocarpa* and either *Sphagna* or 'brown' mosses in floating mats on rather oligotrophic waters, it is unclear whether it is a primary raft former.

Carex diandra is often associated with floating fen mats in the Rocky Mountains, typically with *C. lasiocarpa*, *C. limosa* and *Menyanthes* (Gage & Cooper, 2006a) but is unlikely that this tussock-forming species is a primary raft-former.

Maidencane (*Panicum hemitomum*) is the key species in the formation of thick-mat floatant in the Mississippi Delta, Louisiana, forming a dense mat of very porous root tissue which is considered essential to maintaining the year-round buoyancy of the mats (Mayence & Hester, 2005). According to Sasser et al (2007), *Panicum* is the keystone species in thick-mat floatant formation

²⁶ Ecological Association Comprehensive Report: *Carex lasiocarpa* - (*Carex rostrata*) - *Equisetum fluviatile* herbaceous vegetation. NatureServe. 2007. NatureServe Explorer: An online encyclopedia of life [web application]. Version 6.2. NatureServe, Arlington, Virginia. <http://www.natureserve.org/explorer>

²⁷ Ontario Ministry of Natural Resources: Natural Areas Report – Bonnechere Sedge Meadows, Algonquin Provincial Park. Accessed at: http://nhic.mnr.gov.on.ca/areas/areas_report.cfm?areaid=7736

because “its extensive network of fibrous roots and rhizomes is crucial for building the floating marsh mats... Other marsh plants that commonly occur in this highly buoyant floating mat do not produce the extensive below ground material necessary for thick-mat development”.

Experiments are currently underway to determine whether ‘edge-expanding’ plants such as alligatorweed (*Alternanthera philoxeroides*) or floating pennywort (*Hydrocotyle ranunculoides*) can pioneer lateral expansion of thick-mat flotant, eg by fusing adjacent rafts (Mayence & Hester, 2005).

Dansereau & Segadas-Vianna (1952) described the shrub *Myrica gale* as a pioneer mat former, its root mass being colonised by *Hypnum* and *Sphagnum* species which formed a platform for subsequent invasion of non-aquatic species such as *Chamaedaphne*. They note that the *Myricetum gale* is generally a secondary plant association of floating mires but the shrub will often extend out into open water. *Myrica* is occasionally co-dominant in floating mires with *Chamaedaphne*, as at Leatherleaf Bog in Ontario²⁸ but it is not often described as a primary raft-former. Different growth forms may occur in North America and it is unlikely that *Myrica* would function as a primary raft-former in north-western Europe.

Marsh ferns of the genus *Thelypteris* are mentioned in descriptions of several types of floating wetland including the *plaur* of the Danube Delta (Anon, 1917), riparian floating reedswamp in north-eastern Poland (Kłosowski, 1993), the embalsados of the Pantanal (Potts & Potts, 2004), *Typha* mats in Ka Nui Marsh, Hawai’i²⁹, ‘fern and sedge’ rafts in Namanve Swamp, Uganda (Eggeling, 1935), vegetation rafts on Australian billabongs (Hill et al, 1987), a floating mat fringing a Queensland crater lake (Haberle et al, 2006) and floating mats on Lake Embi, Papua New Guinea (Lane-Poole, undated). *Thelypteris palustris* are also minor components of Louisiana *flotant* (Swarzenski et al, 1991), calcareous floating-mat fens in the Chicago region (Bowles & Jones, 2006), and Minnesota shore fens. *T. palustris* is probably associated primarily with tall, shading vegetation such as mature stands of *Phragmites*; in coastal flotant in Louisiana it is characteristic of the thicket phase which follows colonisation of unburnt rafts by woody shrubs (Battaglia et al, 2007). Whilst they are frequently associated with floating wetlands, it seems unlikely that Thelypterid ferns are primary raft-forming species but their their rhizomatous growth habit may well contribute to raft consolidation.

Kutz (1926) described the role of water horsetail (*Equisetum fluviatile*) in the formation of floating moss mats in turbary pits in central Russia. This does not seem to be reflected elsewhere in the literature, although *E. fluviatile* is common as a (usually) minor component in various floating mat fen communities.

²⁸ Natural Heritage Information Centre, Ontario Ministry of Natural Resources, (online):
http://nhic.mnr.gov.on.ca/areas/areas_report.cfm?areaid=10626

²⁹ http://www.aecos.com/KOOLAU/Kawai_Nui_3.html

8 RAFT FORMING PROCESSES

8.1 Structural buoyancy

In some cases, floating wetlands are primarily (or at least partly) auto-buoyant because vegetation structures provide the necessary flotation. This may be provided by dense fibrous root systems or rhizomes containing extensive air vacuoles (aerenchyma).

Louisiana floating marshes are characterised by (i) a low bulk-density organic substrate free of mineral sediments and (ii) plants with extensive fibrous root systems. In most truly buoyant wetlands, maidencane dominates. This has an extensive, robust root system with below-ground growth comprising at least 90% of total biomass. The dry bulk density of floating wetland substrates sampled by Sasser et al (1996) was always $<0.1 \text{ g/cm}^3$ and as low as 0.03 g/cm^3 .

Floating papyrus and *Miscanthidium* swamps seem to be structurally buoyant due to the interwoven root masses and aerenchymous rhizomes (Azza et al, 2000; Kansime, Saunders & Loisel (2007). *Menyanthes* is an important pioneer raft-builder in northern zones and its inflated rhizomes provide structural buoyancy. This may also apply to mat-forming sedges such as *Carex rostrata* and *C. lasiocarpa*.

Some primary raft-forming species are unlikely to be positively buoyant on their own, eg leatherleaf (Swan & Gill, 1970) and perhaps *Pycnus nitidus* (Ellery et al, 1990). These probably require structural support from other species, sometimes including submerged or floating-leaved water plants. Much remains to be learned about the biomechanics of raft formation.

8.2 Gaseous buoyancy

Hogg & Wein (1988a & b) studied floating *Typha* rafts in an impounded freshwater wetland in New Brunswick, Canada. They found that *Typha* rhizomes provided net buoyancy throughout the growing period, though there was seasonal variation. This structural autobuoyancy appears to be critical during the early stages of floating mat development, "when mats are thin and composed largely of living, below ground organs" (Hogg & Wein, 1988a). However, in older and thicker mats, gaseous buoyancy associated with anaerobic decomposition processes becomes more important. Thus the root mass accounts for only about 10-20% of buoyancy in 40-60 cm thick rafts.

This gaseous buoyancy is influenced by temperature-dependent microbial activity and therefore varies seasonally, with greatest buoyancy in late summer (Hogg & Wein, 1988b). They found that gases - principally methane bubbles trapped within the organic matrix - constituted 13.7% of the total mat volume at 22°C but only 6.2% at 2°C.

Gaseous processes in floating wetlands have been studied by Fechner-Levy & Hemond (1996) at Thoreau's Bog, a Massachusetts schwingmoor. Methane flux was found to be influenced by atmospheric pressure, temperature and watertable elevation. The influence of atmospheric pressure on gas volumes within floating rafts has given rise to tales that the movement and position of mobile floating islands can be used to predict the weather (Van Duzer, 2004).

8.3 Points of nucleation

Several studies have suggested the importance of a point of purchase or nucleation in raft formation. Dansereau & Segadas-Vianna (1952) stated that, in the initial stages of floating mire formation, "The outward extension of the mat over open water is possible only if an already consolidated mass of peat exists or if a rock, a rotting log, or some solid object can serve as an anchoring point". At Harvard Pond, Massachusetts, *Chamaedaphne calyculata* was able to

spread over the surface of an artificial shallow lake from multiple points of establishment on felled tree stumps in the flooded basin (Swan & Gill, 1970). However, the stumps were probably points of origin rather than physical support for the expansion of *C. calyculata*.

In discussing floating wetlands in south-eastern USA, Sklar & van der Valk (2003) suggest that “The formation of plant root matrix islands is initiated by a point of nucleation such as partially submerged, dead tree limbs, trunks or tree rootstocks, pieces of organic substrate or bank debris”.

Petr (2000) records the development of sudd rafts containing *Vossia cuspidata*, *Leersia hexandra* and *Oryza borthii* around drowned tree stems in Volta Lake, Ghana. The same author describes how this ‘suddification’ was centred on the stumps of flooded rubber trees in Sirinumu Reservoir, Papua New Guinea. The Kapowsin Lake floating bog in Washington State (USA) is reported to have formed over a mass of floating logs, penned in behind a “flotilla” of floating timber (Churney, 1996; also referred to by Turesson, 1916).

Nagy & Tuba (2003) describe a pathway to floating mire formation which involved *Sphagna* colonising masses of fibrous, hair-like adventitious roots in flooded willow swamp in Hungary.

8.4 The role of aquatic macrophytes in floating raft formation

Azza et al (2006) suggest that floating raft formation along the shoreline of northern Lake Victoria is initiated when emergent swamp plants invade free-floating macrophyte communities in shallow water. This is followed by detachment of the root mat of emergents from the substratum following flooding.

In the Okovango Delta, the sudd-forming sedge *Pycnus nitidus* requires the support of submerged detritus or masses of the aquatic spike-rush *Websteria confervoides* in order to initiate raft formation (Ellery et al, 1990). In Dutch kragge fens, floating rafts sometimes develop as secondary formations over a platform of floating *Stratiotes aloides*, but the presence of submerged aquatic plants is not essential to kragge development (Van Wirdum, 1995).

In tropical floating wetlands, free-floating water plants such as *Eichhornia*, *Pistia* and *Salvinia* sometimes become sufficiently aggregated to provide a platform for colonisation by sedges or semi-aquatic grasses (eg Hill et al, 1986; ITE/IRSNB, 1996).

At Mud Lake in Washington State, the formation of a *Menyanthes* raft was preceded by development of submerged and floating-leaved vegetation such as *Brasenia schreberi*, *Potamogeton* and *Utricularia* spp (Turesson, 1916).

8.5 Floating islands resulting from uplifted peat masses

Floating islands of varying longevity can form when masses of peat are detached from the shore by storms and then float freely on the surface of lakes. Detached portions of floating or grounded shoreline swamps sometimes form free-floating islands which may eventually coalesce in windward bays (Denny, 1973; Azza et al, 2006). More commonly, buoyant peat masses may rise from the bottom of lakes due to natural processes or following deliberate flooding. Naturally uplifting peat masses known as batteries or pop-ups are important in floating wetland formation in the Okefenokee Swamp and Florida Everglades (Cypert, 1972; Sklar & van der Valk, 2003) and form ‘organic suddes’ in the Okovango Delta (Ellery et al, 1990). Sometimes the rhizomes of water plants bind together submerged peat in a manner which facilitates the uplifting of blocks of material (eg Sklar & van der Valk, 2003; Lodge, 2004; Cowling et al, 1997).

The detachment of vegetated blocks of organic sediment (rather than lateral vegetation spread) appears to be important in the formation of South American embalsados, some (but not all) types of African floating papyrus swamp, plaur in the Danube Delta and thick-mat flotant in the Mississippi Delta. In some cases, it is the rhizome and root mat which uplifts from soft sediment, rather than a block of substrate.

Van Duzer's *bibliography* cites sources referring to floating islands forming as a result of inundation of peatland during the construction of reservoirs in Brazil, Canada, Costa Rica, Finland, Oregon, Russia and the Ukraine. Petr (2000) gives examples of sudd forming in tropical reservoirs in Ghana, Nigeria, Thailand and Papua New Guinea due to the flotation of submerged substrates.

Hogg & Wein (1988b) have described how masses of *Typha* (mainly the hybrid *T. x glauca*) broke free from the substratum following the impoundment and flooding of a Canadian marsh to create a shallow lake. The vegetation formed a floating mat which has remained buoyant since and has shown evidence of succession towards poor-fen.

Flooding of peatland may induce the formation of buoyant peat masses due to methane production in the substrate as organic material decays under anaerobic conditions. At Kis-Balaton in Hungary, re-flooding of a drained wetland led to death and decay of reedswamp vegetation, producing gaseous buoyancy in the substratum (Somodi & Botta-Dukát, 2004).

The Sehestedter Außendeichsmoor on the Waddensee coast in North-west Germany is a relict of the extensive inland peatland which existed prior to the flooding of the Jade basin by repeated storm surges in the Middle Ages. It remains as an ever-diminishing raft of acidic peatland within a saltmarsh landscape, which is lifted by the highest tides. This raft has a unique stratigraphy, with bands of clay intersecting the peat substrate.

8.6 Floating islands on mineral substrates

According to Van Duzer (2004), it has been suggested that the mobile floating island on the Lago di Paterno in Italy, originally described by the Roman author Dionysius, was formed from floating marl or tufa. Van Duzer (2001) suggests that the mobile *Cladium* rafts in the Mexican sinkhole at Zacaton may also be based on tufa (travertine), although tufa deposition is no longer evident at this location. Floating rafts formed by masses of pulverised fuel ash cenospheres are an analogous artificial entity (see Section 9 of this report).

8.7 The influence of wave action

Brunberg & Blomqvist (2000) and Kellner (2003) concluded that floating rafts only formed in smaller lake basins with little wave action in central Sweden. However, they hypothesised that expansion of marginal peatland in larger lakes might eventually facilitate floating raft development as the area of open water shrank. Azza et al (2006) demonstrated that floating mat-forming species predominate in low energy environments around the northern shoreline of Lake Victoria (Uganda). Wind-wave action and water level fluctuations were important controlling factors with mat-forming plants favouring the most sheltered locations with modest water level fluctuations. Denny (1973) also emphasised the importance of sheltered bays for floating swamp formation in an upland lake in Uganda. Swineheart & Parker (2002) found that small, sheltered lake basins in Indiana (USA) favoured the development of floating, peat-forming mats. Dansereau & Segadas-Vianna (1952) also refer to the reduced wind and wave action in sheltered bays, one factor being that the limited aeration allows peat formation on floating rafts.

Kelly & Southwood (2006) report that the outer edges of an artificial vegetated raft at Barton Broad (Norfolk) suffered from wave erosion and had to be re-planted.

8.8 Other factors influencing the formation or degeneration of floating wetlands

Although *phumdis* have proliferated in Loktak Lake in recent years, there has been a simultaneous thinning of those in Keibul Lamjo National Park (KLNP). This is a potential threat to the endemic Sangai deer which depend on the rafts. The phenomenon has been linked to hydrological changes following impoundment of the Loktak system, raised water levels apparently having reduced the availability of nutrients to the rafts in KLNP (Singsit, 2003).

The *Sphagnum*-dominated schwingmoors of the West Midlands Mosses SAC are considered vulnerable to natural succession (colonisation by birch and pine), atmospheric and water-borne nutrient enrichment and recreational disturbance. Mitigation measures have included Management Agreements to reduce agricultural run-off and clear-felling of basin slopes adjoining Chartley Moss to avoid the cycling of airborne nutrients through tree leaf litter³⁰. Wybunbury Moss has been affected by urban effluent and remains vulnerable to eutrophication from agricultural and urban run-off. Eutrophication has led to the degradation of mire surfaces and the localised replacement of *Sphagnum* mire by wet, unstable fen woodland (Hawley et al, 2004). Eutrophication resulting from fish-rearing activities, sewage and agricultural run-off has also led to the degradation of floating mires at Malom Pond in Hungary, including the disappearance of species such as *Menyanthes* which are sensitive to elevated nitrogen levels (Tatár, 2004).

Referring to floating mires in the Pyrenees, Dansereau & Segadas-Vianna (1952) suggest that infiltration of alkaline water can cause disintegration and subsidence of peat-accumulating mats. The same authors also observe that floating mat development may regress if loss of surrounding tree cover removes the protective 'windbreak'.

The effects of airboat use on subarctic floating-mat fens in Alaska have been documented by Racine et al (1998). Airboats scalp the mats to a depth of 30 cm and destroy almost all emergent vegetation, though some regeneration may be possible following the abandonment of trails. In the Rocky Mountains, recreational trampling of floating fen mats has led to compaction of the peat mass, resulting in reduced buoyancy and loss of vegetation cover (Rocchio, 2005).

Krussi & Wein (1988) found floating *Typha* mats in a Canadian impoundment lagoon to be robust: burning did not significantly affect species composition and mats recovered well from temporary draining of the waterbody. The authors concluded that such temporary disturbances were unlikely to interrupt succession to bog since mat building would continue. However, whilst floating-mat vegetation is well-adapted to fluctuations in water level and some types may withstand temporary dewatering, prolonged reduction in lake levels leading to the 'beaching' of floating mats on dry ground will result in their disappearance. This has been shown by Welch (1938) in the context of a 'retrograding' lake hydrosere in Michigan.

Coastal *flotant* in Louisiana can be damaged by wind, tidal and wave action associated with hurricanes. This can cause compression of vegetation mats, piling of material into mounds or the sinking of floating mats as a result of heavy sediment deposition (Lovelace & McPherson, 1995).

The decline of floating mat vegetation in an Australian billabong system – from 31% coverage of the water surface to 5% over a 15 year period - was attributed to the activities of feral Water Buffalo by Hill et al (1981). In the Mississippi Delta Plain there have been major losses of maidencane-dominated thick-mat flotant in recent decades and in some areas this habitat has given way to open water or fragile, spike-rush dominated thin-mat vegetation; between 1968 and

³⁰ SAC data form, accessed at: www.jncc.gov.uk/ProtectedSites/SACselection/n2kforms/UK0013595.pdf

1992, thick-mat flotant decreased from 67% to 19% of wetland vegetation in the Barataria and Terrebonne basins (Sasser et al, 2007). This has been attributed to increased flooding, saltwater intrusion, water quality problems and herbivore grazing, especially by feral Coypu (*Myocaster coypus*, known as Nutria in the USA). Sasser et al (2007) report on experiments to regenerate thin-mat flotant by planting with maidencane and to establish thick-mat flotant on fabricated rafts.

Lambert (1946) warned of the potential for feral Coypu to damage floating reedswamp vegetation in the East Anglian Broads, and her prediction proved to be very true. One of the reasons that conservation bodies are now deploying artificial floating rafts is to restore this floating fringe which has failed to recover since the eradication of Coypu.

Some floating wetlands are prone to invasion by alien plant species. Bowles & Jones (2006) reported that calcareous floating-mat fens in the Chicago region have experienced invasion by alien plants in recent years though this has not affected species composition significantly. Battaglia et al (2007) described the invasion of un-burnt thick-mat flotant in coastal Louisiana by Chinese tallow (*Triadica sebifera*), a non-native sub-shrub, though the ecological impact of this is unclear. *Brachiaria mutica* (California grass), introduced as an aquatic fodder crop, has become an invasive nuisance in Loktak lake, posing a threat to the indigenous vegetation required by *Sangai* and other wildlife in the floating wetland of Keibul Lamjao National Park. Non-native *B. mutica* is also dominant in the floating marsh at Kawai Nui, Hawaii.

9 IMPORTANCE OF FLOATING WETLANDS FOR BIODIVERSITY

The floating *plaur* of Danube Delta provides habitat for breeding wetland birds including 5% of the global population of Dalmatian Pelican on floating islands in Lake Hrecisca alone³¹; it is also used by mammals such as Raccoon Dog, Otter and important populations of the threatened European Mink (Kranz et al, 2001).

Floating rafts or accumulations of debris have been reported as providing nest sites for grebes, divers, terns, rails and pelicans (numerous references in Van Duzer, 2004). On a large lake in Minnesota, almost half the breeding population of Red-necked Grebes (*Podiceps grisegena*) nested colonially on floating mats of *Typha*, in contrast to the normally territorial breeding behaviour of the species (Klatt et al, 2004). In North America, floating bog mats provide particularly favourable nesting habitat for Common Loon/Great Northern Diver (*Gavia immer*) (Evers, 2004). Floating mat wetlands in the Grand Bay Wildlife Management Area, Georgia (USA) provide foraging habitat for several hundred Sandhill Cranes in winter. At the same site, Florida Water Rats (*Neofiber alleni*) inhabit the floating mat³². This IUCN Red Data-listed species, also known as the Round-tailed Muskrat, occurs in similar habitats in the Okefenokee Swamp (Harper, 1920). Floating *Typha* rafts in southern Ontario are widely used by terrestrial mammals such as Raccoons, whose trails provide loci for maintaining plant diversity in these monodominant swamps (Hewitt & Miyanishi, 1997).

The Sangai or Brow-antlered Deer (*Cervus eldi eldi*) is a globally-endangered deer endemic to the floating phumdis of Keibul-Lamjoo National Park in Loktak Lake, Manipur, India (Mukherjee, 1994; Singsit, 2003; Sanjit et al, 2005). It is also known as the 'dancing deer' because of its rhythmic movements over the floating swamp, and its hooves are adapted to moving over the phumdis (Mukherjee, 1994). The survival of the endangered Marsh Deer (*Blastocerus dichotomus*) in the Paraná Delta, Argentina, is closely linked to the floating rafts known as *embalsados*, which are especially important as refugia during floods (Varela et al, 2001; Pralongo et al, 2007). Floating swamps are also important for this species in the wetlands of the Pantanal (Da Silva et al, 2000).

The Yacaré Caiman (*Caiman crocodylus yacare*) is closely associated with floating wetlands in Argentina and Brazil (Da Silva et al, 2000)³³. Floating mats provide important nesting habitats for other crocodylians in the Northern Territories of Australia, Papua New Guinea, Bolivia, Venezuela and the USA (Hill et al, 1981 and references therein).

The floating meadows of the Amazon floodplains provide habitat for various fishes, of which the swamp eels (Synbranchidae) and knifefish (Gymnotidae) are particularly well-adapted to this habitat (Petr, 2000).

The moss *Campylopus turficola* is endemic to Easter Island, where it grows in floating, peat forming mats in volcanic crater lakes (Schlatter, 1993).

There is limited information on the biodiversity interest of floating wetlands in Britain. Schwingmoor at Abbots Moss, Cheshire, is noted for its spider fauna and the presence of scarce Odonata such as the White-faced Dragonfly (*Leucorrhina dubia*) and the Downy Emerald (*Cordulia aenea*) (Ecology Services UK, 2006). White-faced Dragonfly is closely, though not exclusively, associated with floating mires and occurs at all the classic English schwingmoor sites. The money spider *Carorita limnaea* is known in Britain only from *Sphagnum* schwingmoor at Wybunbury Moss and similar lowland mire at Fenn's and Whixhall Moss in Shropshire. It is

³¹ <http://deltassoft.com/danube.htm>

³² http://www.sherpaguides.com/georgia/wildlife_viewing/plantation_trace/51.html

³³ See also species profile at http://www.flmnh.ufl.edu/cnhc/csp_cyac.htm

part of a distinct relict-mire spider assemblage at Wybunbury (Felton & Judd, 1997). The same site is notable for its moths (Lepidoptera), caddis-flies (Trichoptera) and beetles (Coleoptera) (Nature Conservancy Council, 1986). The 10-spotted Pot Beetle (*Cryptocephalus decemmaculatus*) is another speciality of Wybunbury Moss and Chartley Moss (Shropshire). This UK Biodiversity Action Plan priority species has a disjunct distribution in Britain, also occurring in northern Scotland, so it is not restricted to schwingmooren³⁴. However, the isolated populations at Wybunbury and Chartley appear to be genetically divergent from others and have tentatively been classed as 'evolutionary significant units' (Piper & Compton, 2003).

Chartley Moss, Staffordshire, is also noted for its mire invertebrates including the caddis fly *Hagnella clathrata* (Nature Conservancy Council, 1987), a species listed as Endangered in Great Britain (Wallace, 1991). This species also occurs on the Fenns/Whixhall/Bettisfield Moss complex.

Semi-floating fen rafts provide an important locus for rare vascular plants and bryophytes in both British and Dutch turbaries (Wheeler & Shaw, 1995; Van Wirdum, 1995). Indeed, species associated with Norfolk Broads turf ponds such as *Dryopteris cristata* (crested buckler fern) and *Liparis loeselii* (fen orchid) are rare or absent on nearby solid peat surfaces (Wheeler & Shaw, 1995). *Liparis* is very closely associated with buoyant fen rafts, at least in East Anglia (Wheeler et al, 1998).

³⁴ Species Action Plan accessed at <http://www.ukbap.org.uk/UKPlans.aspx?ID=247>

10 ECOSYSTEM FUNCTIONS OF FLOATING WETLANDS

Floating wetlands perform a range of important ecosystem functions as well as providing wildlife habitat. Sudds regulate the hydrograph of the White Nile whilst embalsados regulate the hydrology of Lagunas del Iberá Ramsar Site in Corrientes, Argentina, acting as a valve controlling the throughput of water³⁵. *Phumdis* in Loktak Lake “influence hydrological regimes, harbour rich biodiversity, support productive fisheries and provide several economically important plant species” (Trisal & Manihar, 2004).

Gaudet (1979) found that nitrogen is fixed in appreciable quantities by floating papyrus swamps and concluded that “papyrus swamps effectively extract dissolved nutrients from tropical river systems”; however, such systems are not simply nutrient sinks as subsequent output of organic matter cycles nitrogen back into the waterbody.

“One of the most important functions provided by the Lake Victoria wetlands is the ability to maintain and improve lacustrine water quality” in a catchment of 9 million people where eutrophication is becoming a pressing problem (Kansiime, Saunders & Loiselle, 2007). Threats to these functionally-vital wetlands include pollution, conversion to agriculture, use for landfill or reclamation for urban development. The capacity to attenuate polluted/enriched influent water is greatest when inflow is through the pore spaces in the rhizome mat; this pathway provides much more effective interaction with the vegetation than surface or subsurface flow. With *Miscanthidium*, however, the very dense structure of the mat reduces interaction between the rhizosphere and the water column.

In Loktak Lake, phumdis provide biological sinks for N, P and K and a thick belt of phumdis around the northern part of Loktak “is critical to the maintenance of water quality of the lake by acting as a biological sink to the key nutrients”. Sequestration of water- and sediment- borne nutrients by phumdis in the northern sector of Loktak alone equates to 478.6 tonnes of N, 39.6 tonnes of P and 157.2 tonnes of K per annum (Trisal & Manihar, 2004).

The submerged root and rhizome masses of the floating meadows of the Amazon floodplains provide a rich and productive habitat for invertebrates, thus providing an important food source for small fish, including some economically important species (Petr, 2000). The floating meadows of the Amazon floodplains are subject to periodic break-up and downstream dispersal of portions. This process plays a role in the dispersal of various animals (many references in Van Duzer, 2004) including fish belonging to the families *Cichlidae* and *Anostomidae* (Petr, 2000). When swept through estuaries and out into the ocean, floating rafts are likely to play an important – if rare – role in the dispersal of plants and animals to oceanic islands.

Floating wetlands can have high carbon sequestration potential. The floating papyrus and *Miscanthidium* swamps of Lake Victoria, for instance, store large quantities of C in detritus and peat deposits under anaerobic conditions (Kansiime, Saunders & Loiselle, 2007). High rates of peat accumulation have been reported from floating bog rafts in European cut-over mires (Joosten, 1995), a recently-formed semi-floating *Sphagnum* mat over a platform of *Typha* in an Ohio sand quarry (Andreas & Host, 1983) and from buoyant rush mats in a high altitude Andean peatland (Earle et al, 2003).

³⁵ See Ramsar Site Information Sheet, accessed at: http://www.ramsar.org/ris/ris_argentina_ibera_e.htm

11 MANAGEMENT PROBLEMS ASSOCIATED WITH FLOATING WETLANDS

Masses of buoyant peat arising from the inundation of peatland during reservoir construction can create significant management problems, as indicated by several papers cited in Van Duzer's *Global bibliography* (2004). The significant issue is the emission of methane from these buoyant masses, which can shift a wetland from functioning as a carbon sink to becoming a source of greenhouse gas. Studying an experimentally flooded peatland in Ontario, Saquet (2003) found that 65 to 90% of methane production was oxidised before it was emitted to the atmosphere during pre-flooding conditions, but this figure was only around 30% for the floating peat islands which formed as a result of impoundment.

In North America various management issues arise from floating islands on lakes. According to Belluck (2005), the State of Minnesota issues permits for the removal of floating islands where they create problems for lakeside householders. In Florida, attempts are made to 'steer' floating islands using boats, anchor them into the corners of lakes and block their movement using wooden pilings (Belluck, 2005). A Florida company called Texas Aquatic Harvesting specialise in breaking-up floating rafts using 90-foot weed-cutting boats and floating machines with front-mounted rotary blades (www.texasaquaticharvesting.com; Alam et al, 1996). One floating island which developed following the raising of water levels in a chain of Rhode Island ponds eventually had to be blow up with dynamite (Kelley, 1994).

In Lake Kyoga, Uganda, flooding associated with El Niño in 1997/98 dislocated floating papyrus *sudds* which blocked the lake outlet. This caused a rise in lake level almost 2 m, an increase in surface area of around 10% and an increase in volume of up to 50%³⁶.

Invasive aquatic plants cause extensive problems in wetlands worldwide; amongst the most notorious is the fern *Salvinia molesta*, which is often described as forming mats or rafts. Sometimes coalescent floating masses of *Salvinia* do provide a substrate for successional development of floating wetlands but more typically the species simply occurs in huge aggregations of free-floating individual plants. These can impede navigation, immobilise boat propellers, block irrigation and hydro-electric installations and increase flooding by decreasing flow rates and increasing sediment deposition (McFarland et al, 2004).

At Kawai Nui Marsh in Hawaii, restoration work includes removal of some areas of floating-mat vegetation to create open water (Kailua Bay Advisory Council, 2002). At this site floating wetland formation is at least in part attributable to the invasion of non-indigenous plants and has resulted in the loss of open water habitats.

At Laguna Cartagena National Wildlife Refuge in Puerto Rico, wetland was converted to a permanent lake in 1959 and since then 90% of the 220 acre (89 ha) site has become covered by a thick floating peat mat vegetated with *Typha*, wetland grasses, *Eichhornia* and *Pistia stratiotes* (Ramírez Toro & Minnigh, 1997). This has resulted in a loss of waterfowl and wader habitat, reduction in water storage capacity, blockage of drainage channels (causing flooding in local villages) and threats to human health.

Phumdis have proliferated in Loktak in recent years and now cover more than 70% of the lake, probably because impoundment at the lake outlet prevents the dispersal of disintegrating islands downstream (Sanjit et al, 2005). Environmental problems have included siltation and eutrophication, loss of fish biomass and diversity, loss of other biodiversity and, ironically, loss of the hydraulic head available for power generation (eg Trisal & Manihar, 2004). However, hydrological changes have also resulted in a thinning of the phumdis which are essential to the survival of the endemic Sangai deer. Sustainable management of Loktak is envisaged as

³⁶ Lake Kyoga Integrated Management Project (Uppsala University): <http://www.geo.uu.se/kyoga/kyoga.html>

including selective removal of phumdis, harvesting them for compost or organic fertilisers and protecting them where they play an important role as wildlife habitat or as nutrient sinks (Trisal & Manihar, 2004).

12 USE OF FLOATING MIRES IN PEATLAND RESTORATION

The development of floating rafts of *Sphagnum* has been advocated as a means of restoring cut-over acidic peatlands (eg Smolders et al, 2004; Money, 1995). This is partly because floating substrates could provide favourable hydrological conditions for the re-establishment of peat-building *Sphagnum* vegetation, and partly because floating mires can show very high peat accumulation rates. Joosten (1995) refers to rates of 1,000 – 5,000 kg/ha/yr, which are much higher than long-term accumulation rates for natural, undisturbed mires. He suggests that, “These high accumulation rates may enable the development of sustainable peat ‘production’ techniques in which accumulation in cut-over bogs is enhanced for future peat extraction...”

Money & Wheeler (2004) comment that well-developed examples of floating bog vegetation characterise smaller hand-excavated cuttings dug decades or centuries ago. They conclude that:

“The potential for developing floating bog across areas of commercial worked peatland is uncertain. The requirements for successful floating bog formation are poorly understood and it appears to work in some locations and not others... Consequently, ‘floating bog’ is a ‘risky’ end-point option compared with ‘emergent bog’. Arguably it would be best left to situations where deep inundation is unavoidable.”

In the Netherlands, floating mats of *Sphagnum cuspidatum* have developed over large areas of some commercial cuttings whilst others remain dystrophic lakes. Raft formation apparently depends upon colonisation by appropriate *Sphagna* and the presence of floating peat detached from the cut-over surface after flooding. Peat flotation may be influenced by methane production in the substrate, which is inhibited by low pH or sulphate pollution. Low bicarbonate levels and strongly humified peat may also inhibit raft formation.

According to Money & Wheeler (2004), the efficacy of treatments such as adding lime to peat cuttings to induce peat flotation has not been proven. However, in a short-term (1 year) experiment, Tomassen et al (2003) studied the properties of poorly-humified peat from 4 Dutch cut-over bogs. They found that low nutrient levels and high bulk-density were associated with poor buoyancy whilst very acidic peat only became buoyant when lime was added at a rate of 2 g per kg of fresh peat to raise pH above 4.5. This was attributed to unfavourable conditions for methanogenesis when pH is <4.5. Tomassen et al (2005) showed that methane production rates in peat correlated closely to the pH to bulk density ratio, allowing estimation of the suitability of peat for this method of restoration.

Where fen (alkaline) peat has been extracted, floating mats of *Caricion davalianae* fen communities have been found to develop in highly calcareous but oligotrophic conditions:

“The floating properties of the raft appear to be central in delivering permanently saturated (not inundated) surface conditions which are critical to the development of the vegetation. The potential for actively restoring this type of vegetation to commercially worked peatland is unknown, principally because the mechanisms of raft formation are too poorly understood to be reliably replicated. Vegetation management is required to prevent succession to wet woodland.” (Money & Wheeler, 2004)

Money & Wheeler (2004) summarise a range of proposed mechanisms involved in raft formation including:

- Colonisation of open water from the edges of flooded cuttings
- Uplifting and flotation of bottom-rooting vegetation following flooding

- Formation by *Phragmites* of adventitious roots at surface level
- Coalescence of floating peat

However, they conclude that the mechanisms are too poorly understood to prescribe methods for promoting raft formation.

13 FLOATING ISLANDS ON PULVERISED FUEL ASH (PFA) LAGOONS

PFA is a waste product from coal-burning power stations; some is sold as a secondary aggregate either raw or after processing in lagoons; the unsold residue disposed of in North Yorkshire amounted to 1.4 million tons in 1996-97 (North Yorkshire County Council, 2001). PFA consists mainly of aluminosilicates and in its unamended state is highly alkaline, saline, has minimal nitrogen content and is toxic to plants due to high levels of boron compounds. However, a range of interesting wildlife habitats develop on weathered PFA including orchid-rich grasslands, dune-slack type habitats and reedbeds (Merritt, 1994; Shaw, 1994). The material has sometimes been used to backfill gravel pits to produce shallow water.

1-2% of PFA consists of cenospheres – tiny, hollow, buoyant spheres which rise to the surface when the ash is deposited in wet lagoons. These ‘floaters’ form a scum on the surface which may be colonised by *Phragmites australis*, *Glyceria fluitans* and *Typha latifolia*. During calm weather, patches of vegetated floaters coalesce to form islands (Shaw, 1994).

Shaw comments that, “These early stages can be seen at most PFA lagoons where floaters are allowed to accumulate for any length of time...and the effect could be recreated on any medium-sized lake given an adequate amount of floaters”. Merritt (1994) considered potential limitations of this approach to include the free-floating nature of the islands and access difficulties (preventing active vegetation management). It has been suggested, he states, that masses of floaters could be overlain with nylon netting to produce more robust islands.

Accumulation of organic matter on the surface of the raft allows gradual succession towards woodland and a floating mass of willow-birch woodland developed within 20 years on a lagoon at Gale Common ash disposal site in North Yorkshire (Shaw, 1994). At this site, floating reedbeds drift across the surface of PFA lagoons and provide nesting habitat for a range of wetland birds (M. Hammond, pers obs).

At Welbeck landfill near Wakefield, 22 floating PFA islands were present in 1991; these moved around the lagoon and collided like dodgems to form ovoid or rounded shapes (Shaw, 1994) – very reminiscent of Pliny the Younger’s observations of floating islands in Lake Vadimon (“Each has its own shape and size, but the edges of them are worn away by their frequent collision with the shore and one another”; cited by Munz, 1711).

Sometimes cenospheres are harvested for insulation material, cosmetics manufacture, scientific research and other uses.

14 ARTIFICIAL FLOATING WETLANDS

The idea of creating floating islands is, of course, not a new one: peoples living in wetland environments have created floating or anchored platforms using local plant materials and sediments since prehistoric times. Munz (1711) proposed to utilise knowledge of natural floating islands to produce an artificial example on the Duzent-Teich Lake near Nüremberg. He suggested importing buoyant peat from Friesland, planting it “with rushes, vines, and other similar bonds” and setting it afloat on the lake. “If all these things are carefully arranged...” he suggested, “I see no reason why art could not create a floating islands as good as nature makes”.

Artificial floating wetland systems have been deployed in several countries for habitat creation, fishery enhancement, nutrient sequestration, pollution remediation and erosion control (**Figure 18**). Headley & Tanner (2006) provide a comprehensive review of floating wetland technologies relevant to stormwater treatment. Perhaps one of the most significant uses of floating wetlands in the UK is at Terminal 5, Heathrow Airport (**Figure 19**). Approximately 6,000 m² of floating reed beds are installed within a concrete drainage system to treat stormwater run-off containing glycol derived from de-icing compounds. Other applications include sewage and animal effluent treatment and river quality improvement.

Numerous techniques have been used for the creation of floating wetlands and a number of commercially available systems are available. The most common approach to constructing floating wetlands is to fabricate a buoyant raft or frame supporting a mesh on which plants are grown. Coconut fibre or peat is often used as a growth medium. Buoyancy in such systems is generally achieved through the use of sealed sections of plastic pipe or sealed drums or polystyrene foam pontoons.

A low cost method has been developed in India using naturally buoyant bamboo (**Figures 20 and 21**). A number of companies (eg Bestmann Green Systems, AGA Group) produce modular rafts that can be joined together to form floating wetlands of various shapes and sizes (**Figures 22 and 23**).

A second well-developed approach to the construction of floating wetlands involves the use of a matrix with intrinsic buoyancy which itself serves to support the vegetation. Examples include the spun polyester matrix with injected buoyant polystyrene manufactured by Floating Islands International (USA) (**Figures 24, 25 and 26**) and the floating plastic netting materials produced by the Huck Group (Germany).

The artificial raft should provide buoyancy, support and stability. A larger area of island will be required if tall plants such as common reed are to be subject to windy conditions. The raft should ideally maintain a fixed height above the watertable to prevent inundation of the raft surface. Water logging of porous material (eg wooden floats) may reduce buoyancy and impact on plant growth. In some cases buoyancy is such that terrestrial may be grown on the floating raft structures. In some cases a substrate will be necessary to promote plant growth. This will need to have a limited weight and some means of preventing it being washed away. Established plants may be able to grow hydroponically, obtaining sufficient nutrients direct from the water.

Considerations when determining materials and construction methods to be used for artificial rafts include:

- durability
- functionality
- environmental sensitivity

- weight
- buoyancy
- anchoring
- flexibility
- cost

Box 2: Sources of information on commercial artificial floating wetland technologies

AGA Group (England): www.agagroup.org.uk

Floating Islands International (US based): www.floatingislandinternational.com

Bestmann Green Systems (Germany): www.bestmann-green-systems.com or
www.bestmann-green-systems.com/English.29.0.html

At Barton Broad, Norfolk, a 0.7 ha floating island was constructed using pre-planted, pre-fabricated units in order to cover a navigation hazard. Kelly & Southwood (2006) conclude that this technique was reasonably successful but that a more sheltered location would have been more favourable for vegetation growth. The most successful pre-planted species were *Carex riparia*, *Iris pseudacorus* and *Schoenoplectus lacustris*.

As part of an ecological restoration project at Cockshoot Broad in the Norfolk Broads, an attempt has been made to re-create 'hover' swamp using coir matting. Such vegetation had occurred previously but had died-off due to pollution and historic damage by Coypu. Commercially-available coir mats were planted with *Typha angustifolia* and secured over 20 cm depth of water over mud. Over 500 mats were installed. Initial results have been promising but in summer 2005 there was substantial die-back of *Typha*, which the site manager believed to be due to poor root development and very hot conditions³⁷.

At Cherokee Marsh in Madison, Wisconsin (USA), a deep ditch resulting from engineering works caused erosion of adjacent wetlands and provided a poor habitat for recolonisation of aquatic or emergent vegetation because of the soft, unstable substrate and disturbance by Carp. An attempted solution has been to create a floating platform made from mesh, bailed leaves and willow or aspen logs, over which pre-vegetated coir mats planted with local wetland species have been spread (City of Madison Parks Division, 2002). The outcome of this initiative is not known.

In attempts to 'engineer' restoration of thick-mat *flotant*, Mayence & Hester (2005) highlight three essential attributes: a lightweight organic growth medium, a double layer of mat material to contain the medium and support growth, and a supporting structure to keep the raft continuously close to the water surface. Media containing peat appear to support good plant productivity. Various mat materials are being investigated, primarily coconut fibre/coir-based. Sasser et al (2007) report that successful designs for floating platforms included capped PVC pipes or bamboo frames for buoyancy, wire planting baskets, various artificial substrates to hold the planted maiden and fencing to exclude Coypu/Nutria. These trials have demonstrated the possibility of re-establishing thick-mat flotant on artificial platforms but costings are unclear and it

³⁷ Rick Southwood, Natural England Site Manager for the Broadland Reserves: *pers comm.* (2006)

is as yet uncertain whether expanding and self-sustaining vegetation mats can be established in this way.

15 APPLICATION TO THE QUARRY ENVIRONMENT

Approaches to establishing floating wetlands in the quarry environment may involve;

- Establishment of raft-forming vegetation in shallow water, with the aim of establishing self-maintaining floating mats
- The use of artificial raft structures, either as stand-alone features or to promote the development of floating vegetation which could eventually become auto-buoyant

A number of factors may inhibit natural raft formation, or attempts to stimulate natural raft-forming processes using artificial platforms, in British quarry lakes (box 3).

Box 3: Can British quarry lakes provide suitable conditions for floating wetland development? Some questions requiring further exploration.

Can wave action be sufficiently reduced to allow natural raft formation or expansion?

Would low water temperatures in groundwater-fed lakes inhibit vegetation establishment on planted rafts?

Will near-surface conditions be too aerated to allow peat formation? Would lack of methane production then limit gaseous buoyancy?

Under typical gravel pit conditions, would high nutrient levels inhibit establishment of keystone raft-forming plants such as bobbean (*Menyanthes trifoliata*), marsh cinquefoil (*Potentilla palustris*), bottle sedge (*Carex rostrata*) and slender sedge (*C. lasiocarpa*)?

Can grazing and trampling by waterfowl be controlled effectively?

Artificial platforms

Fabricated rafts have some potential for specific uses in the quarry environment, eg fishery habitat enhancement, small-scale landscaping, polishing effluent water and breaking up large open waterbodies. However, none of the commercially available technologies which we have investigated are likely to be cost-effective for more extensive habitat creation. A standard 4 m² floating island pre-planted, including anchor and grazing protection, as purchased for the field trials cost £430 (exc VAT) plus delivery.

Low cost DIY rafts for re-establishing maidencane flotant have been successfully deployed in Louisiana, with experimental rafts now covering roughly 1 ha (M Materne, pers comm, 13 Feb 2008). These rafts are envisaged as a means of regenerating auto-buoyant, naturally self-maintaining floating wetland and could represent an important way forward. The following issues need to be taken into account when planning for the use of floating wetland technology at a site:

- Growth media and plant establishment
- Biosecurity if pre-planted mats obtained from a nursery
- Securing and mooring the floating wetlands
- Wind and wave issues
- Management requirements

Establishment of a root system prior to installation in open water is seen as key by AGA Group for successful establishment of their floating island technologies. Artificial means may be used to provide this binding and support. However, floating wetlands are dynamic systems and the constraints of non-biodegradable materials on the long-term performance of the island are unknown. In natural systems accumulated organic matter decays to form peat beneath the living root mat and top growth. Weight will gradually increase and unless additional buoyancy develops (eg from gas production) the mat may sink. Many of the natural raft structures mentioned in the literature appear to be in the order of 0.5 to 1 m in thickness. This is potentially a result of material being shed from the base of the floating mat, thereby maintaining its buoyancy. It is unclear whether this is a significant process in the lifecycle of floating rafts and whether an artificial base may restrict weight loss and limit the life span of the raft. This effect has not been reported by AGA from the rafts they have deployed over the last 15 years.

Constructing rafts from biodegradable material is complex as it is difficult to predict the life of the material which is dependent on the site-specific conditions. Artificial material will not degrade but will become encased in the vegetation of the floating raft. A decision is required as to whether this is an acceptable long-term solution.

General considerations

Accurate prediction of quarry lake levels is particularly important when designing lake margins. Health and safety considerations may require a shallow gradient (<1:4) until a water depth of >1.5 m is attained, to prevent anyone wading from suddenly entering deep water. For example an uncertainty in water level of ± 1 m would require the 1:4 slope over a horizontal width of some 18 m. For shallower margins prediction of final water levels becomes even more critical. Costly planting schemes may require repetition if too much or too little inundation occurs. Floating wetlands may therefore be of benefit where final water levels are unknown or likely to fluctuate such as in lakes without a controlling outfall. If a 1 in 4 gradient is assumed then establishment of floating wetland may occur in water depths of <2 m over a horizontal width of some 8m. However, it is essential that floating rafts are not subject to 'beaching' except perhaps for very brief periods.

The timescale over which the floating vegetation rafts develop may be significant compared with timescales appropriate to quarry restoration (< 5 years). However there are indications that raft formation may be rapid in some cases and artificial means could potentially be used to speed up the process.

It is apparent that use of floating wetland restoration techniques will have health and safety implications for operations on the shoreline and within the deeper water.

Grazing and associated disturbance by herbivorous mammals or waterfowl should not be underestimated as a factor controlling the formation of floating wetlands. This is entirely ignored in palaeoenvironmental studies of hydroseral succession but is clearly influential: around 100,000 acres of Louisiana floatant are considered to be impacted by Coypu/Nutria grazing (M Materne, Louisiana State University, pers comm, 13 Feb 2008) whilst the deployment of artificial rafts to restore fringing 'hover' on the Norfolk Broads reflects the failure of riparian floating mats to regenerate naturally following the systemic damage caused by feral Coypu prior to their eradication. Grazing by Greylag and Canada Geese of introduced ancestry and native Coots is well-known as inhibiting the establishment of *Phragmites* reedbeds on restored mineral sites in the UK. Some means of protecting the establishing vegetation is therefore required.

Globally, floating swamp rafts are often characterized by bulky, competitive monocotyledons such as *Typha*, *Phragmites*, papyrus and maidencane. In general these species probably favour more nutrient-rich conditions than the primary raft-formers associated with floating fens and bogs.

However, these buoyant swamp-mats - variously known as hover, plaur, thick-mat flotant, embalsado and sudd – appear to be associated with very specific hydrological and hydrogeological conditions. In general, temperate floating swamps dominated by high-productivity monocotyledons seem to be associated with detachment or uplifting of rooted swamp or formation of a narrow floating riparian/littoral fringe, rather than centripetal invasion of open water. Uplifting of patches of *Phragmites* or *Typha angustifolia* or the formation of floating adventitious root masses by these species does occur in North-western Europe but seems to be associated with small, sheltered basins and the mechanisms are poorly understood, thus unpredictable.

One possible experimental approach might be to pre-establish stands of suitable species (eg *Typha angustifolia*) in a low bulk-density medium such as coir fibre within a textile ‘envelope’. This could potentially be done in-situ in very shallow water when the void is still being pumped dry. It is unknown whether auto-buoyancy could then be achieved when the void is allowed to fill with water.

Natural raft-forming vegetation

Our best advice at this stage is that natural floating-mat forming process could potentially be utilised as follows:

- Choose a sheltered, low-energy environment such as a south-western embayment or a small waterbody fringed by trees.
- Where wave action is significant, establish an offshore breakwater using rubble, dredged material, waste timber, birch faggots or other ‘natural’ material. Fabricated rafts could possibly be anchored along the inner edge of this breakwater to pre-establish floating vegetation, or along the outer edge to buffer wave energy.
- A grid of ‘purchase points’ (hardwood posts, tree stumps/trunks) should be provided in shallow water (shelving to c3 m). Near to the shore, loose ‘fill’ such as brash (from forestry operations) or woodchip might assist the establishment of raft-forming species.
- Plant locally-native raft-forming species such as bogbean, marsh cinquefoil, water horsetail and bottle sedge. Local provenance material (seed or cuttings/offsets) will need to be grown on by a specialist nursery³⁸.

If successful, such an approach could be very beneficial as a method for fen creation, thus contributing to local and national Biodiversity Action Plan targets. In many parts of lowland England, creation of even small areas of floating-mat fen would represent a significant expansion of the local or County resource.

Further research is needed into the availability of PFA cenospheres and their potential use as a floating substrate in quarry lakes, along with any regulatory issues involved. In areas such as North Yorkshire where coal-fired power stations operate there may be considerable potential to use this waste product creatively to form floating islands.

15.1 Discussions with floating wetland practitioners and field trials

Discussions were held with Ash Girdler of AGA Group (Norfolk, England) regarding the design

³⁸ Bought-in plants should be avoided because they do not conserve the local gene pool and are often contaminated with invasive alien plants like *Crassula helmsii*.

and utility of fabricated floating rafts. Telephone interviews were also conducted with M. Materne, of Louisiana State University, regarding the use of artificial rafts to regenerate thick-mat floatant in the Mississippi Delta. Notes on these discussions are provided as **Appendix 3**.

In July 2007, two 2 m x 2 m AGA Group rafts were installed at Nosterfield Quarry, a sand and gravel quarry operated by Tarmac in North Yorkshire (**Figures 27 to 32**). Two more rafts were installed in a former gravel pit at Hatfield Moor, South Yorkshire, part of the Humberhead Peatlands National Nature Reserve. One of each pair was planted with Common reed (*Phragmites australis*) the other with lesser pond sedge (*Carex acutiformis*). Further details of the raft construction and installation procedure are presented in **Appendix 2**. The timeframe of the study has not permitted any meaningful monitoring of the efficacy of these rafts but their installation enabled us to understand the design, budgetary and logistical implications of using these structures. Tim Kohler of Natural England has begun transplanting *Potentilla palustris* into the shoreline inland of the rafts at Hatfield Moor and future monitoring will show whether this pioneer floating mat-former can expand outwards to the anchored rafts.

We concluded that the pre-planted AGA Group rafts represent a very robust, tried and tested design. DIY installation of the component parts is relatively straightforward, although we found it rather difficult to anchor two connected rafts successfully at Nosterfield, which has resulted in some listing of one raft. Professional installation would overcome this problem but increase cost.

16 CONCLUSIONS

The results of the investigations indicate strongly that the creation of areas of artificial wetland, either naturally floating or utilizing engineered flotation, provide potential for ecological enhancement. The study also shows that extensive research and practical studies have been undertaken in this area. However, to date, little practical application has been made in the field of quarry restoration. A significant opportunity has therefore been identified which could greatly increase the ecological value of water-based quarry restorations. With careful thought and planning, quarry sites could contribute to achieving regional BAP habitat objectives.

The review of the published literature indicates that floating wetlands are widespread globally, and form a major component of some aquatic ecosystems, often supporting rich biodiversity. Floating wetlands may cover large areas of open water and are functionally important in wetland ecosystems and wetland economies. Natural or artificial floating islands are used by some indigenous peoples.

Fabricated vegetation rafts are being used for management of the water environment including, wildlife/fishery habitat, erosion control, nutrient sequestration and pollution remediation.

The vegetation of floating wetlands varies across the globe but there are some striking similarities. The floating wetland substrate typically consists of a thick organic mat, entwined with living roots, that rises and falls with the ambient water level. Rafts of floating vegetation are typically formed by invasion of key species from the grounded lake margin out into open water. Another method of formation is via the detachment of established vegetation and/or uplifting of buoyant masses of peat substrate.

Floating wetlands could potentially play a significant role in quarry restoration and further field trials are required. Planting of keystone raft-forming plants along sheltered shorelines of quarries may encourage natural development of floating fen. Reduced wave action and protection from grazing by waterfowl are likely to be essential. Within the UK, bobbean (*Menyanthes trifoliata*), marsh cinquefoil (*Potentilla palustris*) and bottle sedge (*Carex rostrata*) may promote initial raft formation, though it is unclear how well these species would perform in more nutrient-rich waters.

Initial field trials were undertaken at Hatfield Moor nature reserve and Nosterfield Quarry. These trials were intended to obtain a practical insight into the deployment of the rafts using existing 'floating island' technology and inform the planning of further field trials based on additional methods derived during the process of this project. Less than a single growing season was available for the project and longer duration trials will be required to assess the development of the raft forming vegetation. Suggestions are made as to possible applications to the quarry environment as a basis for further applied research. In particular, the potential use of low-cost and/or biodegradable floating platforms to establish auto-buoyant vegetation rafts needs further investigation.

The next stage of the process of determining the feasibility of adopting these measures is to scale-up the field studies which have been undertaken to date. It is recommended that a test site is developed in which to trial the methodologies identified within this report in a realistic field-scale trial.

In practice, and in a quarry setting, the establishment of 'traditional', commercially available floating islands is not likely to be appropriate due to the high cost. Therefore emphasis must be placed upon the development of pragmatic, cost-effective and achievable habitat creation which is within the scope of the quarrying environment. It should be recognized that a trade-off must be made between creating ecologically valuable habitat and acceptable cost. This should be the focus of any subsequent field trials.

17 RECOMMENDATIONS

Based on the literature review of natural systems and discussions with floating wetland experts, quarry operators and nature conservationists a series of recommended field trials have been outlined. It is likely that a minimum of 3 growing seasons would be required to adequately monitor the development of the raft forming vegetation. Sourcing and propagation of appropriate plants would be required and assistance with installation of the necessary site infrastructure. The existing field sites are considered to provide ideal locations for extending the work but additional sites in other parts of the country are also required.

It is recommended that the following items represent a basis for further work.

1. Establish stands of *Typha angustifolia* and *Phragmites* on site in a low bulk-density medium such as coir fibre within a textile 'envelope'. Attempt this in-situ in very shallow water and then allow flooding to assess whether auto-buoyancy can be achieved. Also this approach should be tried on a thin loose substrate overlying an impermeable membrane allowing adequate time for the formation of an interlocking root system to support the plant top-growth before flooding.
2. Construct a breakwater to create a sheltered area (1 Ha) of shallow (<2m) water on the south western margin of a quarry lake. This should incorporate some 100 meters of shoreline which may be subdivided into a series of experimental sections.
3. Establish bobgean (*Menyanthes trifoliata*), marsh cinquefoil (*Potentilla palustris*), bottle sedge (*Carex rostrata*) and slender sedge (*C. lasiocarpa*) along the lake margins and monitor outward expansion. A constant water level or minimum fluctuation is required for this to be successful.
4. Sectioned off areas of the shallows should be filled with loose semi buoyant fill such as brushwood, woodchips and loose peat, to provide buoyancy and support for establishing floating wetland vegetation (**Figure 33**).
5. A sufficient volume of buoyant P.F.A. cenospheres should be purchased for use as in item 4 and also mixed with a suitable substrate as in item 1.
6. Artificial attempts may be made to 'seed' the shallow areas with nuclei of pre-established plants. This may take the form of a 'chequer board' of artificially buoyant structures and fixed stakes. The maximum spreading width of the vegetation across the interstitial spaces of open water is unknown but a best estimate based on experiments in Louisiana would be less than 2 m. It is recommended that both commercially available rafts and the potentially cheaper DIY raft constructions are used.
7. Techniques used for river bank restoration could be trialed on the quarry lake margins. This would involve the use of pre-planted coir pallets or coir rolls along the shore or immediately off-shore on artificial floating rafts. Brush-wood bundles would be installed in the shallow water to trap silt and reduce circulation of colder water from the main lake.
8. Where already present at a site the use of fast growing invasive species may be considered as a rapid means of generating natural floating support structures for colonisation by later (more important) wetland species.
9. A detailed cost efficiency study should be undertaken of the different options tried, including nursery, construction, installation and management costs. This should also include an assessment of the additional mineral potentially released by the utilisation of the new techniques.

The pioneering experiments suggested may represent a world first in wetland habitat creation and potentially provide a cost effective method of creating high quality BAP habitat.

18 REFERENCES

- Acton, A. (2004). NVC survey of the non-SAC part of Clais Dhearg Site of Special Scientific Interest. Scottish Natural Heritage Commissioned Report No. 067 (ROAME N° F03LG13).
- Alam, S.K., Arger, L.A. & Rosegger, T.M. (1996). The effects of mechanical harvesting of floating plant tussock communities on water quality in Lake Istokpoga, Florida. *Lake and Reservoir Management*, **12** (4): 455-461.
- Allen, L., Johnson, J.D. & Vujnovic, K. (2004). Small patch communities of Colin-Cornwall Lakes Wildland Provincial Park. Report prepared for Parks and Protected Areas, Alberta Community Development: Edmonton.
- Anderson, R.L., Foster, D.R. & Motzkin, G. (2003). Integrating lateral expansion into models of peatland development in temperate New England. *Journal of Ecology*, **91**: 68-76.
- Andreas, B.K. & Bryan, G. R. (1990). The vegetation of three *Sphagnum*-dominated basin-type bogs in northeastern Ohio. *Ohio Journal of Science*, **90** (3): 54-66.
- Andreas, B.K. & Host, G.E. (1983). Development of a *Sphagnum* bog on the floor of a sandstone quarry in northeastern Ohio. *Ohio Journal of Science*, **83** (5): 246-253.
- Anon (1917). Notices of publications on foreign vegetation. Review of: Pallis, M. (1916). The structure and history of Plav: the floating fen of the delta of the Danube. *Linnean Society Journal of Botany*, **43**: 233-290. In: *Journal of Ecology*, **5** (1): 52-53.
- Askari, M. (2003). Iraq's ecological disaster. *International Review*: accessed at www.int-review/terr36a.html
- Azza, N., Denny, P., Van de Koppel, J. & Kansime, F. (2006). Floating mats: their occurrence and influence on shoreline distribution of emergent vegetation. *Freshwater Biology*, **51** (7): 1286-1297.
- Azza, N.G.T., Kansime, F., Nalubega, M. & Denny, P. (2000). Differential permeability of papyrus and *Miscanthidium* root mats in Nakivubo swamp, Uganda. *Aquatic Botany*, **67**: 169-178.
- Bailey, J. & Quigley, R. (2007). *Nellie Longarms*. Brookmark Publications: Nantwich.
- Barbour, M.G. & Billings, W.D. (2000). *North American terrestrial vegetation*. 2nd edition. Cambridge University Press: Cambridge.
- Battaglia, L.L., Denslow, J.S. & Hargis, T.G. (2007). Does woody species establishment alter herbaceous community composition of freshwater floating marshes? *Journal of Coastal Research*, **23** (6): 1580-1587.
- Bedford, B.L., Zimmerman, E.H. & Zimmermann, J.H. (1974). *The wetlands of Dane County, Wisconsin*. Dane County Regional Planning Commission.
- Beilfuss, R., Moore, D., Bento, C. & Dutton, P. (2001). Patterns of vegetation change in the Zambezi Delta, Mozambique. Working Paper N° 3, Program for the Sustainable Management of Cahora Bassa Dam and the Lower Zambezi Valley.

- Bellamy, D.J., Bradshaw, M.E., Millington, G.R. & Simmons, I. G. (1966). Two Quaternary Deposits in the Lower Tees Basin. *New Phytologist*, **65**, (4): 429-442.
- Belluck, P. (2005). Drifting into a debate: disagreement on whether to tether island that floats. *New York Times*, Sunday November 6, 2005.
- Beltman, B., Van den Broek, T., Barendregt, A., Bootsma, M.C. & Grootjans, A.P. (2001). Rehabilitation of acidified and eutrophied fens in The Netherlands: effects of hydrologic manipulation and liming. *Ecological Engineering*, **17** (1): 21-31.
- Beltman, B., Van den Broek, T. & Bloemen, S. (1995). Restoration of acidified rich-fen ecosystems in the Vechtplassen area: successes and failure. pp 273-286 in Wheeler et al (1995).
- Beltman, B., Van den Broek, T., Bloemen, S. & Witsel, C. (1996). Effects of restoration measures on nutrient availability in a formerly nutrient-poor floating fen after acidification and eutrophication. *Biological Conservation*, **78** (3): 271-277.
- Bigley, R.E. & Hull, S.W. (2000). *Recognising wetlands and wetland indicator plants on forest lands in Washington*. Washington State Department of Natural Resources, Scientific Support Section: Olympia, WA.
- BirdLife International (2007). BirdLife's online World Bird Database, Version 2.1. BirdLife International: Cambridge, UK. Accessible at: www.birdlife.org/datazone/sites
- Blankenburg, J. & Tonniss, W. (eds) (2004). *Guidelines for wetland restoration in peat cutting areas*. Results of the BRIDGE Project. Institute of Soil Technology: Bremen.
- Bootsma, M.C., Van den Broek, T., Barendregt, A. & Beltman, B. (2002). Rehabilitation of acidified floating fens by addition of buffered surface water. *Restoration Ecology*, **10** (1): 112-121.
- Bowles, M. & Jones, M. (2006). Trends of change in composition and structure of Chicago region wetland vegetation. *Chicago Wilderness Journal*, **4** (3): 25-34.
- Bowles, M. & Jones, M. (2007). The Prairie-Wetland vegetation continuum in the Chicago Region of Northeastern Illinois. *Ecological Restoration*, **25** (1): 29-39.
- Brandt, L.A., Martin, G.L. & Mazzotti, F.J. (2006). Topography of pop-up bayhead tree islands in Arthur R. Marshall Loxahatchee National Wildlife Refuge. *Florida Scientist*, **69** (1). Accessed at <http://www.apr.allenpress.com>
- Brunberg, A-C. & Blomqvist, P. (2000). Post-glacial, land rise-induced formation and development of lakes in the Forsmark area, central Sweden. Svensk Kärnbränslehantening AB, Technical Report TR-00-02.
- Bunting, M.J., Morgan, C.R., Bakel M. Van & Warner, B.G. (1998). Pre-European settlement conditions and human disturbance of a coniferous swamp in southern Ontario. *Canadian Journal of Botany*, **76**: 1770-1779.
- Burns, F.L., Moresby, J.F. & Peterson, J.A. (1985). The floating islands of Pirron Yallock, Victoria. *Australian Society of Limnology Bulletin*, N^o 10: 15-32.

Campbell, D.R., Duthie, H.C. & Warner, B.G. (1997). Post-glacial development of a kettle-hole peatland in southern Ontario. *Écoscience*, **4** (3): 404-418.

Carpenter, K. (2005). Effects of adding sediment to a freshwater thin mat floating marsh. Masters thesis submitted to Louisiana State University, December 2005.

Chicago Wilderness Consortium (1999). *Biodiversity Recovery Plan*. CWC: Chicago. Accessible at: <http://www.chicagowilderness.org/biodiversity/coalition/index.cfm>

Churney, M. (1996). *Bogs, meadows, marshes and swamps: a guide to 25 wetland sites of Washington State*. The Mountaineers Books: Seattle.

City of Madison Parks Division (2002). Cherokee Marsh wetlands restoration begins. *Park News*, Spring 2002.

Cooper, D., Wolf, E. & Gage, E. (2007). Plant establishment for wetland reclamation: a review of plant establishment techniques and species tolerances for water level and salinity. Appendix D in CEMA (2007). *Guideline for wetland establishment on reclaimed oil sand leases*. Revised edition. Cumulative Environmental Management Association: Fort McMurray, Alberta.

Cowling, R.M., Richardson, D.M. & Pierce, S.M. (1997). *Vegetation of Southern Africa*. Cambridge University Press: Cambridge.

Craine, S.I. (2003). *Rhynchospora indundata* (Oakes) Fern. (inundated beak-rush): conservation and research plan for New England. Report to New England Wildflower Society, Framingham MA.

Crushell, P.H., Schouten, M.G.C., Smolders, A.J.P., Roelofs, J.G.M. & Giller, P.S. (2006). Restoration of minerotrophic vegetation within an Irish raised bog soak system. *Biology and Environment: Proceedings of the Royal Irish Academy*, **106B** (3): 371-385.

Cypert, E. (1972). The origin of houses in the Okefenokee Prairies. *American Midland Naturalist*, **87** (2): 448-458.

Dansereau, P. & Segadas-Vianna, F. (1952). Ecological study of the peat bogs of eastern North America, 1: structure and evolution of vegetation. *Canadian Journal of Botany*, **30** (4): 490-520.

Da Silva, M.P., Mauro, R., Mourão, G. & Coutinho, M. (2000). Distribuição e quantificação de classes de vegetação do Pantanal através de levantamento aéreo. *Revista Brasileira de Botânica*, **23** (2).

Dekker, S.C., Barendregt, Bootsma, M.C. & Schot, P.P. (2005). Modelling hydrological management for the restoration of acidified floating fens. *Hydrological Processes*, **19**: 3973-3984.

Denny, P. (1973). Lakes of south-western Uganda, II: Vegetation studies on Lake Bunyonyi. *Freshwater Biology*, **3**: 123-135.

Earle, L.R., Warner, B.G. & Aravena, R. (2003). Rapid development of an unusual peat-accumulating ecosystem in the Chilean Altiplano. *Quaternary Research*, **39**: 2-11.

Ecology Services UK Ltd (2006). Abbots Moss Management Plan. Prepared for Cheshire Wildlife Trust.

Edwards, L. (2003). The Okefenokee Swamp. Article on Georgia Botanical Society website. Accessed at: <http://www.gabotsoc.org/articleOkefenokee2003.htm>

Eggeling, W.J. (1935). The vegetation of Namanve swamp, Uganda. *Journal of Ecology*, **23** (2); 422-435.

Eggers, S. D., & Reed, D. M. (1997). *Wetland plants and plant communities of Minnesota and Wisconsin*. 2nd edition. U.S. Army Corps of Engineers, St. Paul District. Jamestown, North Dakota: Accessible at Northern Prairie Wildlife Research Center Online: <http://www.npwrc.usgs.gov/resource/plants/mnplant/index.htm>

Ellery, K., Ellery, W.N., Rogers, K.H. & Walker, B.H. (1990). Formation, colonisation and fate of floating sudds in the Maunachira River system of the Okavango Delta, Botswana. *Aquatic Botany*, **38**: 315-329.

English Nature (1998). *Meres and Mosses Natural Area profile*. Natural Area Profile N° 27. English Nature: Peterborough.

Evers, D. C. (2004). Status assessment and conservation plan for the Common Loon (*Gavia immer*) in North America. US Fish and Wildlife Service: Hadley, MA.

Fechner-Levy, E.J. & Hemond, H.F. (1996). Trapped methane volume and potential effects on methane ebullition in a northern peatland. *Limnology and Oceanography*, **41** (7): 1375-1383.

Felton, C. & Judd, S. (1997). *Carorita limnaea* (Araneae: Linyphiidae) and other Araneae at Wybunbury Moss, Cheshire - a unique refuge for two relict species of spider in Britain. *Bulletin of the British Arachnological Society*, **10** (8): 298-302.

Finlayson, C.M., Lowry, J., Bellio, M.G., Nou, S, Pidgeon, R., Walden, D., Humphrey, C. & Fox, G. (2006). Biodiversity of the wetlands of the Kakadu Region, northern Australia. *Aquatic Science*, **68**: 374-399.

Foss, P. (2007). Study of the extent and conservation status of springs, fens and flushes in Ireland, 2007. Internal report for the National Parks & Wildlife Service: Dublin.

Foster, D.R. & King, G.A. (1984). Landscape features, vegetation and developmental history of a patterned fen in south-eastern Labrador, Canada. *Journal of Ecology*, **72**: 115-143.

French, C.N. & Moore, P.D. (1986). Deforestation, *Cannabis* cultivation and schwingmoor formation at Cors Llyn (Lynn Mire), central Wales. *New Phytologist*, **102**: 469-482.

Gage, E. & Cooper, D.G. (2006a). *Carex diandra* Schrank (lesser panicled sedge): a technical conservation assessment. USDA Forestry Service, Rocky Mountain Region (on-line). Accessed at: <http://www.fs.fed.us/r2/projects/scp/assessments/carexdiandra.pdf>

Gage, E. & Cooper, D.G. (2006b). *Carex limosa* L. (mud sedge): a technical conservation assessment. USDA Forestry Service, Rocky Mountain Region (on-line). Accessed at: <http://www.fs.fed.us/r2/projects/scp/assessments/carexlimosa.pdf>

Gantes, P., Sánchez Caro, A., Momo, F., Casset, M.A. & Torremorel, A. (2005). An approximation to the nitrogen and phosphorus budgets in floating soils of a subtropical peatland (Iberá, Argentina). *Ecological Modelling*, **186** (1): 77-83.

Gaudet, J.J. (1979). Seasonal changes in nutrients in a tropical swamp: North Swamp, Lake Naivasha, Kenya. *Journal of Ecology*, **67**: 953-981.

Giller, K.E. & Wheeler, B.D. (1986). Past peat cutting and present vegetation patterns in an undrained fen in the Norfolk Broadland. *Journal of Ecology*, **74**: 219-247.

Giller, K.E. & Wheeler, B.D. (1988). Acidification and succession in a flood-plain mire in the Norfolk Broadland. *UK Journal of Ecology*, **76**: 849-866.

Godwin, H. & Vishnu-Mittre (1975). Studies of the post-glacial history of British vegetation: XVI: Flandrian deposits of the fenland margin at Holme Fen and Whittlesey Mere, Hunts. *Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences*, **270** (N° 909): 561-604.

Green, B.H. & Pearson, M.C. (1968). The ecology of Wybunbury Moss, Cheshire, I: the present vegetation and some physical, chemical and historical factors controlling its nature and distribution. *Journal of Ecology*, **56** (1): 245-267.

Green, B.H. & Pearson, M.C. (1977). The ecology of Wybunbury Moss, Cheshire, II: Post-glacial history and the formation of the Cheshire mere and mire landscape. *Journal of Ecology*, **65** (3): 793-814.

Greenlee, J. & Jones, M. (2000). Ecological inventory of wetland sites in the Thompson Chain of Lakes and vicinity. Unpublished report to the Montana Department of Fish, Wildlife and Parks. Montana Natural Heritage Program: Helena.

Haberle, S.G., Tibby, J., Dimitriadis, S. & Heijnis, H. (2006). The impact of European occupation on terrestrial and aquatic ecosystem dynamics in an Australian tropical rainforest. *Journal of Ecology*, **94**: 987-1002.

Haberyan, K.A., Horn, S.P. & Umaña, G. (2003). Basic limnology of fifty-one lakes in Costa Rica. *Revista de Biología Tropical*, **51** (1).

Hammond, M. (2007a). Habitat loss in the Swalke and Ure Washlands since 1700, with an analysis of extinctions from the local flora. Report to North Yorkshire County Council and English Nature.

Hammond, M. (2007b). *Sphagnum* mire development in a railway borrow pit in East Yorkshire. pp 41-49 in Meade & Humphries (2007).

Hanganu, J., Grigoraş, I., Ştefan, N., Sărbu, I., Dubyna, D., Zhmud, E., Menke, U. & Dorst, H. (2002). *Vegetation of the Biosphere Reserve "Danube Delta"*. Directorate-General of Public Works and Water Management: Lelystad (Netherlands).

Haraguchi, A. (1991a). Effects of water-table oscillation on redox property of peat in a floating mat. *Journal of Ecology*, **79**: 1113-1121.

Haraguchi, A. (1991b). Effect of flooding - drawdown cycle on vegetation in a system of floating peat mat and pond. *Ecological Research*, **6** (3): 247-263.

Haraguchi, A. (1996). Rhizome growth of *Menyanthes trifoliata* L. in a population on a floating peat mat in Mizorogaike Pond, central Japan. *Aquatic Botany*, **53**: 163-173.

- Haraguchi, A. & Matsui, K. (1990). Nutrient dynamics in a floating mat and pond system with special reference to its vegetation. *Ecological Research*, **5** (1):63-79.
- Harper, F. (1920). The Florida water-rat (*Neofiber alleni*) in Okefinokee Swamp, Georgia. *Journal of Mammology*, **1** (2): 65-66.
- Hawley, G., Ross, S., Shaw, S., Taylor, K., Wheeler, B., Worrall, P. (2004). *Nutrient enrichment of basin fens – options for remediation*. English Nature Research Report N° 610. English Nature: Peterborough.
- Hayden, M.J. & Ross, D.S. (2005). Denitrification as a nitrogen removal mechanism in a Vermont peatland. *Journal of Environmental Quality*, **34**: 2052-2061.
- Headley, T.R. & Tanner, C.C. (2006). Application of floating wetlands for enhanced stormwater treatment: a review. NIWA Client Report HAM2006-123, prepared for Auckland Regional Council (New Zealand). National Institute of Water and Atmospheric Research Ltd: Hamilton.
- Hemond, H.F. (1980). Biogeochemistry of Thoreau's Bog, Concord, Massachusetts. *Ecological Monographs*, **50** (4): 507-526.
- Hemond, H.F. (1983). The nitrogen budget of Thoreau's Bog. *Ecology*, **64** (1): 99-109
- Hewitt, N. & Miyanishi, K. (1997). The role of mammals in maintaining plant species richness in a floating *Typha* marsh in southern Ontario. *Biodiversity and Conservation*, **6** (8): 1085-1102.
- Hill, R., Webb, G.J.W. & Smith, A.M.A. (1987). Floating vegetation mats on a floodplain billabong in the Northern Territory of Australia. *Hydrobiologia*, **150**: 153-164.
- Hogg, E.H. & Wein, R.W. (1988a). The contribution of *Typha* components to floating mat buoyancy. *Ecology*, **69** (4): 1025-1031.
- Hogg, E.H. & Wein, R.W. (1988b). Seasonal changes in gas content and buoyancy of floating *Typha* mats. *Journal of Ecology*, **76**: 1055-1068.
- Huffman, R.T. & Lonard, R.I. (1983). Successional patterns on floating vegetation mats in a Southwestern Arkansas bald cypress swamp. *Castanea*, **48** (2): 73-78.
- Hughes, R.H. & Hughes, J.S. (1992). *A directory of African wetlands*. World Conservation Union & United Nations Environment Programme.
- Illinois Department of Natural Resources (1997). *The Fox River Basin: an inventory of the region's resources*. Critical Trends Assessment program, Illinois Department of Natural Resources Office of Realty and Environmental Planning. Accessed at: <http://dnr.state.il.us/orep/C2000/assessments/FRP/page1.htm>
- Institute of Terrestrial Ecology/Institut Royal des Sciences Naturelles de Belgique (1996). *Habitats of South America*. European Union Life Project report.
- Irving, S.J.E. & Meadows, M.E. (1997). Radiocarbon chronology and organic matter accumulation at Vankervelsvlei, near Knysna, South Africa. *South African Geographical Journal*, **79**, 101–105.
- Islam, T. & Atkins, P. (2007). Indigenous floating cultivation: a sustainable agricultural practice in the wetlands of Bangladesh. *Development in Practice*, **17** (1): 130-136.

- Joosten, J.H.J. (1995). Time to regenerate: long-term perspectives of raised bog regeneration with special emphasis on palaeoecological studies. pp. 379-404 in Wheeler et al (1995).
- Judziewicz, E.J. (ed) (2001). *Plants of Wisconsin: natural communities*. On-line, accessed at <http://wisplants.uwsp.edu>
- Kailua Bay Advisory Council (2002). Kawai Nui Marsh restoration under way. *Laha nā Mea Hou o Ko'olau Poko*, **2** (1): 1-2.
- Kansiime, F., Saunders, M.J. & Loiselle, S.A. (2007). Functioning and dynamics of wetland vegetation in Lake Victoria: an overview. *Wetlands Ecology and Management*: online, DOI 10.1007/s11273-007-9043-9.
- Katz, N.J. (1926). *Sphagnum* bogs of central Russia: phytosociology, ecology and succession. *Journal of Ecology*, **14**: 177-202.
- Kelley, M.L. (1994). The infamous floating island of Lonsdale. *Old Rhode Island Magazine*, September 1994. Accessed at: <http://www.quahog.org/factsfolklore/index.php?id=116>
- Kellner, E. (2003). Wetlands – different types, their properties and functions. Svensk Kärnbränslehantening AB, Technical Report TR-04-08.
- Kelly, A. & Southwood, R.R. (2006). The creation of a floating island of native vegetation at Barton Broad, Norfolk, England. *Conservation Evidence*, **3**: 73-74.
- Klatt, P.H., Nuechterlein, G.L. & Buirton, D. (2004). Frequency and distribution of behaviour of red-necked grebes breeding colonially and in classic territories. *Behaviour*, **141** (3): 263-277.
- Kłosowski, S. (1993). The shore vegetation in selected lakeland areas in northeastern Poland. *Hydrobiologia*, **251**: 227-237.
- Kranz, A., Polednik, L. & Gotrea, V. (2001?). Conservation of the European Mink (*Mustela lutreola*) in the Danube Delta. *Scientific Annals of the Danube Delta Institute for Research and Development*, 2000-2001: 124-129.
- Krusi, B.O. & Wein, R.W. (1988). Experimental studies on the resiliency of floating *Typha* mats in a freshwater marsh. *Journal of Ecology*, **76**: 60-72.
- Kyambadde, J., Kansiime, F., Gumaelius, L. & Dalhammar, G. (2004). A comparative study of *Cyperus papyrus* and *Miscanthidium violaceum*-based constructed wetlands for wastewater treatment in a tropical climate. *Water Research*, **38** (2): 475-485.
- Lambert, J.M. (1946). The distribution and status of *Glyceria maxima* (Hartm.) Holmb. in the region of Surlingham and Rockland Broads, Norfolk. *Journal of Ecology*, **33**: 230-267.
- Lamers, L.P.M., Smolders, A.J.P. & Roelofs, J.G.M. (2002). The restoration of fens in the Netherlands. *Hydrobiologia*, **478**: 107-130.
- Lane-Poole, C. (undated). Floating islands of Lake Embi. MS, 1922-1925? Accessed at: http://www.botanicus.org/primeocr/botanicus7/b13116836/31753003450407/31753003450407_0032.txt

- Lewis, F.J., Dowding, E.S. & Moss, E.H. (1928). The vegetation of Alberta: II, the swamp, moor and bog forest vegetation of central Alberta. *Journal of Ecology*, **16**: 19-70.
- Lodge, T.E. (2004). *The Everglades Handbook: understanding the ecosystem*. 2nd edition. CRC Press.
- Lovelace, J.K. & McPherson, B.F. (1995). Effects of Hurricane Andrew (1992) on wetlands in southern Florida and Louisiana. In: *National water summary on wetland resources*. United States Geological Survey Water Supply Paper 2425. USGS: Pittsburgh. Accessed at: <http://water.usgs.gov/nwsum/WSP2425/andrew.html>
- Lynn, L.M. (1984). The vegetation of Little Cedar Bog, southeastern New York. *Bulletin of the Torrey Botanical Club*, **111** (1): 90-95.
- Macek, P & Lepš, J. (2007). Environmental correlates of growth traits of the stoloniferous plant *Potentilla palustris*. *Evolutionary Ecology* [Online First]. DOI: 10.1007/s10682-007-9235-z.
- Mallison, C.T., Stocker, R.K. & Cichra, C.E. (2001). Physical and vegetative characteristics of floating islands. *Journal of Aquatic Plant Management*, **39**: 107-111.
- Magyari, E., Sümegi, P., Braun, M., Jakab, G. & Molnár, M. (2001). Retarded wetland succession: anthropogenic and climatic signals in a Holocene peat bog profile from north-east Hungary. *Journal of Ecology*, **89**: 1019-1032.
- Mayence, C.E. & Hester, M.W. (2005). Study examines techniques for restoring maidencane-dominated thick-mat floating marsh (Louisiana). *Ecological Restoration*, **23** (4): 272-273.
- Maxwell, C.J. & Tyler, P.A. (2006). Recolonisation of Lagoon of Islands, Tasmania, by *Baumea arthrophylla*: the first step in regeneration of a unique ecosystem? *Papers and Proceedings of the Royal Society of Tasmania*, **140**: 31-34.
- McFarland, D.G., Nelson, L.S., Grodowitz, Smart, R.M. & Owens, C.S. (2004). *Salvinia molesta D.S. Mitchell (Giant Salvinia) in the United States: a review of species ecology and approaches to management*. Aquatic Plant Control Research Program: ERDC/EL SR-04-2. U.S. Army Corps of Engineers: Washington DC.
- McKnight, D., Thurman, E.M., Wernshaw, R.L. & Hemond, H. (1985). Biogeochemistry of aquatic humic substances in Thoreau's Bog, Concord, Massachusetts. *Ecology*, **66** (4): 1339-1352.
- Meade, R. & Humphries, N. (eds) (2007). *Minerals extraction and wetland creation*. Natural England: Peterborough.
- Meade, R. & Wheeler, B.D. (2007). Raised bogs from gravel pits? Experiences at Hatfield Moors, South Yorkshire. pp 41-49 in Meade & Humphries (2007).
- Merritt, A. (1994). *Wetlands, industry and wildlife – a manual of principles and practices*. Wildfowl & Wetlands Trust: Slimbridge.
- Millington, R.J. (1954). *Sphagnum* bogs of the New England Plateau, New South Wales. *Journal of Ecology*, **42** (2): 328-344.

Mires Ecology Working Group, Masaryk University (undated). Horské mokřady Bulharska (mountain wetlands of Bulgaria). Accessed at: <http://www.sci.muni.cz/botany/mirecol/bulgaria.php>. [Includes English language version].

Money, R.P. (1995). Re-establishment of a *Sphagnum*-dominated flora on cut over lowland raised bogs. pp 405-422 in Wheeler et al (1995).

Moore, P.D. (1978). Studies in the vegetational history of Mid-Wales, V: Stratigraphic and pollen analysis of Llyn Mire in the Wye Valley. *New Phytologist*, **80**: 281-302.

Muller, F. (2006). Management of grazing in mires of the French Basque country. pp. 16 in Heikkilä, R. & Lindholm, T. (eds). *Restoration and conservation of mires*. Abstracts of the 12th International Mire Conservation Group. Biennial Symposium in Tammela, Finland 2006. Finnish Nature Conservation Association: Oulu.

Mukherjee, R.P. (1994). Brow-antlered deer, *Cervus eldi eldi*, of Manipur. *ENVIS Newsletter* (Zoological Society of India), **2** (1): 2-3.

Munz, G.C. (1711). *Exercitatio academica de insulis natantibus*. Trans. in Van Duzer (2004): pp 1-34.

Nagy, J., Molnár, A, Cserhalmi, D., Szerdahelyi, T. & Szirmai, O. (2007). The aims and results of the nature-protection management of the north-east Hungarian mires. Proceedings of the VI Alps-Adria Scientific Workshop. *Cereal Research Communications*, **35** (2): 813-816.

Nagy, J. & Tuba, Z. (2003). A preliminary report on a new type of floating mire from Hungary. *Annales Ser. Hist. Nat.*, **13** (1): 77-82.

Natural Heritage Advisory Council (2003). *Oregon Natural Heritage Program, 2003*. Department of State Lands: Salem.

Nature Conservancy Council (1983). Site of Special Scientific Interest citation: Clarepool Moss, Shropshire.

Nature Conservancy Council (1986). Site of Special Scientific Interest citation: Wybunbury Moss, Cheshire.

Nature Conservancy Council (1987). Site of Special Scientific Interest citation: Chartley Moss, Staffordshire.

Neff, K.L. & Vankat, J.L. (1982). Survey of the vegetation and flora of a wetland in Kiser Lake State Park, Champaign County, Ohio. *Ohio Journal of Science*, **82** (5): 252-259.

New Hampshire Natural Heritage Bureau (2006). *Visiting New Hampshire's biodiversity: Philbrick-Cricenti bog*. New Hampshire Division of Forests and Lands: Concord.

Nolfo-Clements, L.E. (2006). Vegetative survey of wetland habitats at Jean Lafitte National Historical Park and Preserve in Southeastern Louisiana. *Southeastern Naturalist*, **5** (3): 499-514.

North Yorkshire County Council (2001). North Yorkshire Waste Local Plan (revised deposit draft). NYCC: Northallerton.

Ochsenschlager, E. (1998). Life on the edge of the marshes. *Expedition*, **40** (2): 29-40.

O' Mahony, T. (2001). A report on the Flora of Cork (H3-H5), 2000. *Irish Botanical News*, N° 11 (April 2001): 42-50.

Petr, T. (2000). *Interactions between fish and aquatic macrophytes in inland waters: a review*. FAO Fisheries Technical Paper N° 396. Food & Agriculture Organisation: Rome.

Piper, R.W. & Compton, S.G. (2003). Subpopulations of *Cryptocephalus* beetles (Coleoptera: Chrysomelidae): geographically close but genetically far. *Diversity & Distribution*, **9** (1): 29-42.

Pott, A. & Pott, V.J. (2004). Features and conservation of the Brazilian Pantanal wetland. *Wetlands Ecology and Management*, **12**: 547-552.

Pratolongo, P., Kandus, P. & Brinson, M.M. (2007). Net aboveground primary productivity and soil properties of floating and attached freshwater tidal marshes in the Río de la Plata estuary, Argentina. *Estuaries and Coasts*, **30** (4): 618-626.

Racine, C.H. & Walters, J.C. (1994). Groundwater-discharge fens in the Tanana lowlands, Interior Alaska, USA. *Arctic & Alpine Research*, **26** (4): 418-426.

Racine, C.H., Walters, J.C. & Jorgenson, M.T. (1998). Airboat use and disturbance of floating mat fen wetlands in Interior Alaska, USA. *Arctic*, **51** (4): 371-377.

Ramírez Toro, G.I. & Minnigh, H.A. (1997). Drainwaters: biological responses to water quality. Colegio de Ingenieros y Agrimensores de Puerto Rico. Preservación del Ambiente y el Control de la Contaminación : Eslabones Indispensables para el Futuro de las Américas. San Juan, June 1997. Accessed at: www.bvsde.paho.org/bvsaidis/puertorico/lvii.pdf

Ratcliffe, D. (ed). (1977a). *A nature conservation review: The selection of biological sites of national importance to nature conservation in Britain*. Volume 1. Cambridge University Press: Cambridge.

Ratcliffe, D. (ed). (1977b). *A nature conservation review: site accounts*. Volume 2. Cambridge University Press: Cambridge.

Rauch, S., Hemond, H.F. & Peucker-Ehrenbrink, B. (2004). Source characterisation of atmospheric platinum group element deposition into an ombrotrophic peat bog. *Journal of Environmental Monitoring*, **6**: 335 – 343.

Rodwell, J.S. (ed) (1991-2000). *British plant communities*. 5 vols. Cambridge University Press: Cambridge. [Includes vol. 2: *Mires and heaths* (1991) and vol. 4: *Aquatic communities, swamps and tall-herb fens* (1995)]

Robichaud Collins, B. and Anderson, K. (1994). *Plant communities of New Jersey: a study in landscape diversity*. Rutgers University Press: New Brunswick.

Rocchio, J. (2005). *Rocky Mountain subalpine-montane fen ecological system: ecological integrity assessment*. Colorado Natural Heritage Program: Colorado State University, Fort Collins.

Roulet, N.T. (1991). Surface level and water table fluctuations in a subarctic fen. *Arctic and Alpine Research*, **23** (3): 303-310.

Russell, R.J. (1942). Flotant. *Geographical Review*, **32** (1): 74-98.

- Salett, M. (2002). A natural history of bogs and acidic fens of southern New England. *Conservation Perspectives*, Summer 2002 (on-line).
- Sanjit, L., Bhatt, D., Sharma, R.K. (2005). Habitat heterogeneity of the Loktak lake, Manipur. *Current Science*, **88** (7): 1027-1028.
- Saquet, M.A.M. (2003). Greenhouse gas flux and budget from an experimentally flooded wetland using stable isotopes and geochemistry. Masters thesis, University of Waterloo, Ontario.
- Sasser, C.E., Gosselink, J.G., Swenson, E.M., Swarzenski, C.M. & Leibowitz, N.C. (1996). Vegetation, substrate and hydrology in floating marshes in the Mississippi River delta plain wetlands, USA. *Vegetatio*, **122**: 129-142.
- Sasser, C.E., Holm, G.O. Jr., Visser, J.M. & Swenson, E.M. (2005). Thin-mat floating marsh enhancement, demonstration project TE-36. Final Report. Coastal Ecology Institute, Louisiana State University; Baton Rouge.
- Sasser, C.E., Materne, M.D., Visser, J.M., Holm, G.O. & Evers, E. (2007). Restoring freshwater floating marsh in coastal Louisiana. *Louisiana Agriculture*, **50** (2): 14-18.
- Schessl, M. (1999). Floristic composition and structure of floodplain vegetation in the northern Pantanal of Mato Grosso, Brazil. *Phyton: Annales Rei Botanicae*, **39**: 303-336.
- Schiesari, L., Zuanon, J., Azevedo-Ramos, C., Garcia, M., Gordo, M., Messias, M. & Monteiro Viera, E.M. (2003). Macrophyte rafts as dispersal vectors for fishes and amphibians in the Lower Solimões River, Central Amazon. *Journal of Tropical Ecology*, **19**: 333-336.
- Schlatter, R. (1993) Chilean territories. In Scott, D. A. (1993).
- Scott, D.A. (ed) (1993). *A directory of wetlands in Oceania*. Wetlands International.
- Segadas-Vianna, F. (1951). A phytosociological and ecological study of cattail stands in Oakland County, Michigan. *Journal of Ecology*, **39**: 316-329.
- Seymour, C. (2001). Saharan flooded grasslands. WWF Ecoregion Profile (online). Accessed at: www.worldwildlife.org
- Shaw, P. (1994). Orchid woods and floating islands – the ecology of fly ash. *British Wildlife*, **5** (3): 149-157.
- Singsit, S. (2003). The dancing deer of Manipur. *From the Wild* (Wildlife Institute of India Newsletter), **10** (3):1-4.
- Sklar, F.H. & van der Valk, A. (eds) (2003). *Tree islands of the Everglades*. Springer Publications.
- Smolders, A.J.P., Tomassen, H.B.M., Lamers, L.P.M., Lomans, B.P. & Roelofs, J.G.M. (2002). Peat bog restoration by floating raft formation: the effects of groundwater and peat quality. *Journal of Applied Ecology*, **39** (3): 391-401.
- Somodi, I. & Botta-Dukát, Z. (2004). Determinants of floating island vegetation and succession in a recently flooded shallow lake, Kis-Balaton (Hungary). *Aquatic Botany*, **79**: 357-366.

Southern, W., Ash, J., Brodie, J. & Ryan, P. (1986). The flora, fauna and water chemistry of Tagimaucia crater, a tropical highland lake and swamp in Fiji. *Freshwater Biology*, 16 (4), 509–520.

Symoens, J.J. (ed) (1988). *Vegetation of inland waters*. Handbook of Vegetation Science, 15/1. Kluwer Academic Publishers: Dordrecht.

Swan, J.M.A. & Gill, A.M. (1970). The origins, spread and consolidation of a floating bog in Harvard Pond, Petersham, Massachusetts. *Ecology*, 51 (5): 829-840.

Swarzenski, C.M., Swenson, E.M., Sasser, C.E. & Gosselink, J.G. (1991). Marsh mat flotation in the Louisiana Delta Plain. *Journal of Ecology*, 79: 999-1011.

Swineheart, A.L. & Parker, G.R. (2000). Palaeoecology and development of peatlands in Indiana. *The American Midland Naturalist*, 4: 267-297.

Taaffe, G. (2000). Floating island a relic of a long-gone geologic age. *The Japan Times*, Thursday Nov. 23, 2000. Accessed on-line at: <http://search.japantimes.co.jp/fe20001123gt.html>

Tallis, J.H. (1973). The terrestrialisation of lake basins in North Cheshire, with special reference to the development of 'Schwingmoor' structure. *Journal of Ecology*, 61 (2): 537-567.

Tatár, S. (2004). Antropogén eredetű beavatkozások és terhelések hatása a vere-segyházi Malom-tó úszólápi és parti vegetációjára. *Természetvédelmi közlemények*, 2004 (No. 11): 149-158. [Impacts of human activities on floating mires of Malom Pond at Vere-segyház, Hungary] English language abstract accessed at CAB Abstracts: <http://www.cababstractsplus.org/google/abstract.asp?AcNo=20053128994>

Tomassen, H.B.M., Smolders, A.J.P., Herk, J.M. van, Lamers, L.P.M. & Roelofs, J.G.M. (2003). Restoration of cut-over bogs by floating raft formation: an experimental feasibility study. *Applied Vegetation Science*, 6 (2): 141-152.

Tomassen, H., Smolders, A., Lamers, L. & Roelofs, J. (2005). Development of floating rafts after the rewetting of cut-over bogs: the importance of peat quality. *Biogeochemistry*, 71 (1): 69-87.

Town of Provincetown Land Bank Committee (2000). Shank Painter Pond Wildlife Sanctuary management plan. Accessed at: <http://www.provincetowngov.org/plan/osshank/oshank.html>

Trisal, C.L. & Manihar (eds) (2004). *Loktak: the atlas of Loktak Lake*. Wetlands International & Loktak Development Authority: New Dehli & Imphal.

Turesson, G. (1916). *Lysichiton camtschatcense* (L) Schott, and its behavior in *Sphagnum* bogs. *American Journal of Botany*, 3 (4): 189-209.

Tyler, P.A. (1976). Lagoon of Islands, Tasmania – death knell for a unique ecosystem? *Biological Conservation*, 9 (1): 1-11.

Van Diggelen, R., Molenaar, W.J. & Kooijman, A.M. (1996). Vegetation succession in a floating mire in relation to management and hydrology. *Journal of Vegetation Science*, 7: 809-820.

Van Duzer, C. (2001). Preliminary note on the floating islands of Zacaton sinkhole, Mexico. *Aquaphyte Online*, Winter 2001. Accessed at: <http://aquat1.ifas.ufl.edu/aq-w01-2.html>

- Van Duzer, C. (2004). *Floating islands: A global bibliography*. Cantor Press: Los Altos Hills.
- Van Duzer, C. (2006). *Addenda to Floating islands: A global bibliography*. Cantor Press: Los Altos Hills.
- Van Wirdum, G. (1995). The regeneration of fens in abandoned peat pits below sea level in the Netherlands. pp 251-272 *in*: Wheeler et al (1995).
- Varela, D., Gagliardi, F., D'Alessio, S., Lartigua, B., Aprile, G. & Mónaco, C. (2001). Conservation of Marsh Deer in Paraná Delta, Argentina. *Deer Specialist Group News*, N° 16: 6-8. World Conservation Union: Montevideo.
- Verhoeven, J.T.A., Koerselman, W. & Beltman, B. (1988). The vegetation of fens in relation to their hydrology and nutrient dynamics: a case study. pp 249-282 *in* Symoens (1988).
- Visser, J.E., Sasser, C.E., Charbreck, R.H. & Linscombe, R.G. (2000). Marsh vegetation types of the Chenier Plain, Louisiana, USA. *Estuaries*, **23** (3): 318-327.
- Wallace, I.D. (1991). *A review of the Trichoptera of Great Britain*. Research & Survey in Nature Conservation N° 32. Nature Conservancy Council: Peterborough.
- Warner, B.G., Kubiw, H.J. & Hanf, K.I. (1989). An anthropogenic cause for quaking mire formation in southwestern Ontario. *Nature*, **340**: 380-384.
- Warner, B.G. & Rubec, C.D.A. (1997). *The Canadian wetland classification system*. 2nd edition. Wetlands Research Centre: Waterloo, Ontario.
- Welch, P.S. (1938). A limnological study of a retrograding bog lake. *Ecology*, **19** (3): 435-453.
- Wells, C. (2001). *A survey of the peat stratigraphy of seven 'bog woodland' sites in Scotland*. Wet Woods LIFE Project. Scottish Natural Heritage Commissioned Report F01PA10. SNH: Edinburgh.
- Wetzel, R.G. (1983), *Limnology*. 2nd edition. Saunders College Publishing: Fort Worth.
- Wheeler, B.D., Gowing, D.J.G., Shaw, S.C., Mountford, J.O. & Money, R.P. (2003). *Ecohydrological guidelines for lowland wetland plant communities*. Environment Agency – Anglian Region. Edited by Brookes, A.W., José, P.V. & Whiteman, M.I.
- Wheeler, B.D., Lambley, P.W. & Geeson, J. (1998). *Liparis loeselii* (L.) Rich in eastern England: constraints on distribution and population development. *Botanical Journal of the Linnean Society*, **126** (1-2): 141-158.
- Wheeler, B.D. & Proctor, M.C.F. (2000). Ecological gradients, subdivisions and terminology of north-west European mires. *Journal of Ecology*, **88**: 187-203.
- Wheeler, B.D. & Shaw, S.C. (1995). Focus on fens – controls on the composition of fen vegetation in relation to restoration. pp 49-72 *in* Wheeler et al (1995).
- Wheeler, B.D., Shaw, S.C., Fojt, W.J. & Robertson, R.A. (eds) (1995). *Restoration of temperate wetlands*. John Wiley & Sons: Chichester.

Whinham, J., Hope, G.S., Clarkson, B.R., Buxton, R.P., Alspach, P.A. & Adam, P. (2003). *Sphagnum* peatlands in Australasia: their distribution, utilisation and management. *Wetlands Ecology and Management*, **11**: 37-49.

Whinham, J. & Hope, G.S. (2005). The Peatlands of the Australasian Region. pp 397-433n: Steiner, G.M. (ed). *Mires - from Siberia to Tierra del Fuego*. Biologiezentrum der Oberoesterreichischen Landesmuseen, Neue Serie 35: Linz.

White, G. & Gilbert, J. (eds) (2003). *Habitat creation handbook for the minerals industry*. RSPB: Sandy.

Wiegers, J. (1990). Kragge-woodlands in the Netherlands as a new community-type within the *Alnion glutinosae*. *Plant Ecology*, **89** (1): 79-85.

Wilcox, D.A. & Simonin, H. (1988). The stratigraphy and development of a floating peatland - Pinhook Bog, Indiana. *Wetlands*, **8**: 75-91.

FIGURES

**APPENDIX 1:
VERNACULAR NAMES OF VASCULAR PLANTS REFERRED TO IN THIS REPORT**

<i>Acer rubrum</i>	red maple
<i>Alnus glutinosa</i>	alder
<i>Althernanthera? nodiflora</i>	
<i>Aster borealis</i>	
<i>Baumea arthropphylla</i>	
<i>Betula pubescens</i>	downy birch
<i>Bidens cernua</i>	nodding bur-marigold
<i>Brachiaria mutica</i>	California grass
<i>Brasenia schreberi</i>	water-shield
<i>Calamagrostis canadensis</i>	Canadian small-reed (Am. blue-joint grass)
<i>Calistemon viridiflorus</i>	
<i>Calla palustris</i>	
<i>Calorophus minor</i>	
<i>Cannabis sativa</i>	hemp
<i>Carex appressa</i>	
<i>Carex aquatilis</i>	water sedge
<i>Carex atherodes</i>	slough sedge
<i>Carex diandra</i>	lesser tussock sedge
<i>Carex gaudichaudiana</i>	
<i>Carex lasiocarpa</i>	slender sedge
<i>Carex limosa</i>	bog sedge
<i>Carex magellanica</i>	tall bog sedge
<i>Carex prairea</i>	
<i>Carex riparia</i>	greater pond sedge
<i>Carex rostrata</i>	bottle sedge
<i>Carex thunbergii</i>	
<i>Carex utriculata</i>	beaked sedge
<i>Chamaedaphne calyculata</i>	leatherleaf
<i>Chorisandra australis</i>	
<i>Cicuta maculate</i>	water hemlock
<i>Cicuta virosa</i>	cowbane
<i>Cladium mariscoides</i>	
<i>Cladium mariscus</i>	great fen-sedge/saw-sedge
<i>Coix aquaticus</i>	
<i>Commelina diffusa</i>	
<i>Cynodon sp.</i>	
<i>Cyperus haspan</i>	dwarf papyrus
<i>Cyperus giganteus</i>	
<i>Cyperus papyrus</i>	papyrus
<i>Cyperus platystilis</i>	
<i>Decodon verticillatus</i>	swamp loosestrife
<i>Drosera rotundifolia</i>	round-leaved sundew
<i>Dryopteris cristata</i>	crested buckler fern
<i>Echinochloa polystachya</i>	
<i>Echinochloa scabra</i>	
<i>Equisetum fluviatile</i>	water horsetail
<i>Eriocaulon sikokianum</i>	
<i>Eriophorum angustifolium</i>	common cotton-grass
<i>Eriophorum chamissonis</i>	cotton-grass
<i>Eriophorum vaginatum</i>	haretail cotton-grass
<i>Eupatorium perforatum</i>	

<i>Fuirena robusta</i>	
<i>Glyceria fluitans</i>	flote-grass
<i>Glyceria maxima</i>	reed sweet-grass
<i>Hippuris vulgaris</i>	marestail
<i>Hydrocotyle ranunculoides</i>	floating pennywort
<i>Hydrocotyle vulgaris</i>	marsh pennywort
<i>Hymenachne acutigluma</i>	
<i>Hymenochaeta grossa</i>	
<i>Hypericum virginicum</i>	
<i>Ipomea aquatica</i>	
<i>Iris pseudacorus</i>	yellow flag iris
<i>Isachne globosa</i>	
<i>Leersia hexandra</i>	cut-grass
<i>Lepironia articulata</i>	
<i>Liparis loeselii</i>	fen orchid
<i>Ludwigia ascendens</i>	
<i>Lysimachia thrysisflora</i>	tufted loosestrife
<i>Menyanthes trifoliata</i>	bogbean (Am. buckbean)
<i>Miscanthidium violaceum</i>	
<i>Morella cerifera</i>	wax myrtle
<i>Myrica gale</i>	sweet gale/bog myrtle
<i>Nuphar variegata</i>	bullhead lily
<i>Nymphoides indica</i>	water hearts
<i>Oryza borthii</i>	
<i>Oryza perennis</i>	
<i>Oryza sativa</i>	
<i>Osmunda regalis</i>	royal fern
<i>Oxychloe andina</i>	
<i>Panicum hemitomum</i>	maidencane
<i>Phragmites australis</i>	common reed
<i>Phragmites karka</i>	
<i>Phragmites mauritianus</i>	
<i>Pistia stratiodes</i>	water lettuce
<i>Potentilla palustris</i>	marsh cinquefoil (Am. marsh five-fingers)
<i>Pycneus nitidus</i>	
<i>Restio gracilis</i>	
<i>Restio tetraphyllus</i>	
<i>Rhynchospora fauriei</i>	
<i>Saccharum latifolium</i>	
<i>Sagittaria arifolia</i>	
<i>Sagittaria lancifolia</i>	
<i>Sagittaria latifolia</i>	
<i>Salix candida</i>	
<i>Salix pedicellaris</i>	
<i>Scheuchzeria palustris</i>	Rannoch rush
<i>Schoenoplectus californicus</i> ssp. <i>Tatora</i>	tatora reed
<i>Schoenoplectus lacustris</i>	common club-rush
<i>Schoenoplectus tabernaemontani</i>	grey club-rush
<i>Scirpus californicus</i>	
<i>Scirpus validus</i>	
<i>Scolochloa festucacea</i>	
<i>Sium sauve</i>	
<i>Sparganium angustifolium</i>	? bur-reed
<i>Stratiotes aloides</i>	water soldier

<i>Taxodium distichum</i>	bald cypress
<i>Thelypteris confluens</i>	a marsh fern
<i>Thelypteris interrupta</i>	a marsh fern
<i>Thelypteris palustris</i>	a marsh fern
<i>Thelypteris striata</i>	a marsh fern
<i>Triadica sebifera</i>	Chinese tallow
<i>Typha angustata</i>	reedmace
<i>Typha angustifolia</i>	lesser reedmace
<i>Typha domingensis</i>	reedmace
<i>Typha latifolia</i>	greater reedmace
<i>Typha orientalis</i>	reedmace
<i>Urochloa mutica</i>	
<i>Utricularia intermedia</i>	? bladderwort
<i>Utricularia minor</i>	lesser bladderwort
<i>Vaccinium microcarpum</i>	
<i>Vaccinium oxycoccus</i>	cranberry
<i>Vossia cuspidata</i>	
<i>Websteria confervoides</i>	
<i>Zizania latifolia</i>	

APPENDIX 2: FIELD TRIALS - RAFT INSTALLATION DETAILS

Site visits were undertaken and floating islands installed on 23/08/07 at Hatfield Moor Nature Reserve and at Nosterfield Quarry. Details of the field work are presented below.

Four floating 'eco islands' were purchased from AGA Group and delivered, by 4WD and trailer, to the Hatfield Moor Nature Reserve (HMNR) and Tarmac's Nosterfield Quarry (TNQ) on 23/08/07. Installation at HMNR was undertaken by P Ellis (Hafren Water) and T Kohler (Natural England) and at TNQ by P Ellis and M Hammond.

Each island comprised 4 m² of 75 mm² galvanised steel mesh (dia 3 mm) supported by 10 cm diameter plastic floats along each outer edge. The floats were formed from black plastic waste pipe thermally sealed at each end and bolted (10 mm dia) together to form a square. The floats were attached to the mesh using 10 mm thick cable ties (a minimum of 3 per side).

Once the raft was laid within the water, 4 pre-planted coir pallets were laid on the surface. Each pallet measured 80 cm by 125 cm and was approximately 7 cm thick. The pallets comprised an outer net of loose woven (2.5 cm squares) coir (coconut fibre) stuffed with loose coir fibre. The pallets are biodegradable and contain no substrate or fertiliser, all nutrients being derived by the plants from the underlying water. At each site one floating island comprised Phragmites (reed) and the other lesser pond sedge. Each pallet contained 12 plants which had been grown for 10-12 weeks within a polytunnel and water trough at the AGA Nursery at Merton in Norfolk. The plants are sufficiently advanced such that significant root growth was observed through the base of the pallet. Care is taken within the enclosed growing environment to ensure no unwanted species (eg insects, snails) are imported with the pallets. For larger scale projects ideally the plants used are of local provenance. Pallet weight increases significantly with water content from ~10-15 kg dry weight to ~30-40 kg wet. Drainage of the pallets is therefore required before transport.

The anchor system for each island comprised a chain shackled to and drawn tight between 2 of the opposing floats. The centre of the chain is connected by a swivel to 4 mm diameter steel cable, the length of which is dependent on water depth. The base of the cable is attached to 2 (20 x 40 cm) builders' blocks. The anchor is floated on the raft to the appropriate position before being dropped.

In order to prevent damage to the seedlings from grazing geese etc a bird protection cage was installed above the pallets. This comprised segments (base and 4 sides) of 75 mm square galvanised mesh joined together with cable ties.

At the HMNR the islands were linked together and anchored in ~1 m of water, ~5 m from the shore. The trial location is in the southwestern corner of the lake sheltered from the prevailing westerly winds.

At TNQ the islands were linked together and anchored within ~0.5 m of water, ~8 m from the shore. The trial location is within shallow embayment in the southwestern corner of Kiln Lake, sheltered from the prevailing wind.

APPENDIX 3: DETAILS OF DISCUSSIONS WITH FLOATING ISLAND SPECIALISTS

A site visit was made to the AGA group's plant nursery on 31/08/07. AGA is currently the main UK supplier of floating island technology and discussions were held on the potential to develop natural floating wetland systems.

Report on meeting and site visit at Plant Nursery, Merton, Norfolk on 31st August 2007

Present: Mr Ash Girdler, AGA Group
Dr Paul Ellis, Hafren Water

Applicability of technology to gravel pits and natural systems

The application of floating island technology and coir pallet planting has been under development by the AGA Group for the last 15 years, initially on the basis of improving the quality of fisheries. Other applications have included improvement of water quality, habitat creation and erosion control.

The underlying principal is that robust tussock/raft-forming species of plants tolerant of waterlogged conditions are grown within pallets of coir fibre. These are subsequently placed upon a floating structure comprised of a 2 x 2 m square section of steel mesh supported by plastic floats along each side. Of critical importance is the growth of an adequate root system within the coir mat substrate prior to flotation. This allows the plant to survive the initial change in conditions and develop growth during the first summer season. Inevitably pallets that do not become established during the initial growing season will never recover or develop subsequently. AGA report that this phenomenon has been observed for example within a large raft comprised of 4 adjacent, connected floating islands, growth may fail on one corner raft and despite vigorous growth on the adjacent rafts no further growth or colonisation of the failed raft was ever observed. This was attributed to wave action and upwelling through the base of the coir mat preventing successful root development. In exposed locations with reaches in excess of ~600 m, wave action can be a significant problem (eg in a coastal setting) and prevent successful establishment of floating islands. AGA considered that difficulty in establishing initial root systems would be a major barrier to the successful development of natural raft-forming vegetation away from an artificial 'starter' island. Phragmites had been observed to develop up to 1 m from the sides of an artificial island after approximately 3 years. However, by the 4th year the vegetation became waterlogged and the excess weight tore the excess away. Under natural conditions this may lead to self-setting and colonisation of other locations. However, under conditions common in gravel pits where there is little, if any, suitable marginal substrate AGA considered it unlikely that the detached vegetation would survive and colonise. AGA indicated that many natural floating islands are generally formed in-situ on suitable substrate over a long time frame allowing large interconnecting root systems to develop and hold material (and gas) at a suitably low density to promote buoyancy. These islands are then forcibly detached by water action, to form mature sustainable natural floating systems.

Several ideas were discussed for the development of floating wetlands within a quarry setting. AGA indicated that in general gravel pits represent impoverished environments in terms of suitable substrates for the development of aquatic plants – macrophytes. Without these plants and the zoo plankton that develop within the plant root system the ponds tend to be algae-dominated and the biological water quality generally low. This is particularly relevant to lakes intended for use as fisheries which require macrophytes to support the higher levels of the food chain. Establishment of marginal vegetation is often difficult in a gravel pit setting and the use of pre-planted coir pallets or coir rolls along the shore or immediately off-shore on floating islands could rapidly establish and promote increased biological water quality and growth of the fish population. However, given the often large areas of open water the cost of using pre-planted

coir pallets may be prohibitive. AGA indicated that a 1 m width of margin vegetation around a lake would significantly improve biological lake water quality and habitat for fish spawning.

The use of a checker board approach was discussed, ie having pre-planted floating islands interspersed with areas of open water or bare mesh and allowing natural raft-forming processes to infill the intervening areas. AGA indicated that in their opinion growth across open water was unlikely and that a substrate and buoyant support would be required. If a mesh and coir mat was to be installed anyway, then the additional cost of pre-establishing the plants would probably be justified.

As a cost saving measure to produce large stands of reedbed it was suggested to AGA that mesh and floats could be installed in an area on-site prior to flooding as part of progressive restoration. Reeds could be introduced and allowed to colonise across the top of the 'beached' floating islands.

Flooding of the area would be initiated subsequent to establishment of a good root system and the island floated. AGA considered this unlikely to work due to the potential trauma sustained by the root system as the plants were ripped upwards from the basal substrate. However, it is considered that this idea may be worth pursuing further given the potential to create large areas of floating vegetation in-situ.

AGA noted that care is required to prevent encroachment by terrestrial plants into lake margins which may prevent development of marginal aquatic vegetation.

AGA indicated that laying pre-planted coir pallets directly onto an old lake bed had proved very successful in colonising intermediate areas. Such a direct use may be applicable to silt lagoon restoration. Floating reedbeds may also be applicable in an active silt lagoon setting where water level control is still not finalised but progressive restoration is desired.

AGA site

The AGA plant nursery is located at Merton in Norfolk, the site has a large selection of ponds and wetland areas which originally formed settlement lagoons for treatment (silt settlement) of wash water from the adjacent vegetable processing facility. Plants are grown within series of multi-span poly tunnels containing a plastic-lined, water-filled inset covering the majority of the floor area. The water is supplied from a borehole on-site. The coir mats are laid within the water-filled troughs remaining saturated while plants grow and form sufficient root systems. Seeds are collected from plant stock in the surrounding lakes, propagated in cells and transferred to root trainers over the course of approximately 1 year. From the root trainers the plants are inserted into the coir pallets where approximately 4 months is required to establish suitable root growth for external application. During the summer period temperatures in the multi-span are often in the order of 100°F. If a client wishes to provide their own seed, then final deployment of floating islands may require up to a 2-year lead time.

Biosecurity

In order to prevent the spread of non-native plant and insect species, careful attention is given to biosecurity at the site. Seeds used are collected from ponds at the nursery. Plants are grown inside the multi-spans with the doors closed. Coir pallets provide a sterile substrate. A sterile water system is provided by the site borehole. In general the plants most used on the floating islands are common to most parts of the UK, including lesser and greater pond sedge and common reed.

The raft technology has been developed until the anticipated life of the structure is in excess of 30-40 years. The floatation booms are constructed of UV-resistant HDPE, ultrasonically welded to prevent leakage. A wall thickness of 5 mm is used to prevent damage from air rifle pellets and

consequent sinking of the raft. Industrial gabion mesh is used with a triple coating and a lifespan in excess of 35 years. The coir matting is designed to rot away and form a substrate which is then sustained by continued growth and shedding of vegetation from the established plants. To date the oldest installed floating island is some 15 years old. Floating islands have been adopted to be used as tern nesting platforms. Recycled plastic mats are incorporated in the design and covered in a layer of gravel.

For floating islands to be installed in exposed areas AGA consider it essential to put the islands in place during April to allow the maximum chance for the plants to establish before the onset of harsher winter conditions.

Vegetation growth is more rapid increase of shallow water in which water circulation is generally restricted allowing an increase in water temperature. AGA indicated growth is likely to improve up to a maximum water temperature of 27°C.

It may be possible to promote the formation of warms hallow areas by the use of brushwood bundles. These will reduce circulation of colder water from the main lake which is often only at 10°C, groundwater temperature. In addition the reduced water velocities will promote silt settlement and eventual infilling and wetland formation. AGA use hardwood (hazel or beech) bundles of approximately 2 m in length and 0.3 m diameter. A layer of brushwood may be installed leaving a depth of approximately 8" of open water above. A floating island may then be installed at the outer edge of the bundle, reducing circulation from the main lake and potentially allowing colonisation from the island back towards the shore across the support provided by the brushwood bundles.

AGA costs

Standard 1 m² of planted coir pallet = ~£25

Contract grow from specific seed = £32-£37

Brushwood bundle = £10

Standard 4 m² floating island pre-planted, including anchor and grazing protection (as purchased for the field) = £430 each

Delivery = dependent on location

Grazing trials and fish predation protection

AGA considers protection from grazing water fowl essential to successful floating island use. Gabion mesh is used to cover the pallets and is left in place for the life of the island. After initial plant growth the mesh is no longer visible and acts as a continued deterrent to geese. It has been observed that ducks are content to use the floating islands as nest sites, up on top of the grazing protection mesh. A finer mesh cage has been used successfully on the underside of floating islands as a refuge for smaller fish from predation by cormorants.

Floating island species used by AGA

Sedges (*Carex*) are the most robust of the plants used by AGA for floating islands including:

- Greater pond sedge (*Carex riparia*) - commonly used
- Lesser pond sedge (*Carex acutiformis*) – commonly used
- Slender sedge (*Carex lasiocarpa*) – occasionally used, found in low nutrient wetlands
- Bottle sedge (*Carex rostrata*)

Reed Mace (*Typha*) (sometimes incorrectly called bulrush) is not commonly used, as has previously given poor results on the artificial floating islands

T. angustifolia - lesser reedmace, T.latifolia - (greater) reedmace

Reeds. Common Reed (*Phragmites australis*) is often used and gives rapid growth but prefers

to grow in larger island groupings due to wind action on its long stems

Bog bean (Menyanthes trifoliata) is not commonly used on the islands.

Other species include:

- Club-rushes *Schoenoplectus*
- Rush - *Juncus* (lots of different species, soft rush, *Juncus effusus*, being the most common)
- Yellow flag iris (*Iris pseudacorus*)
- Reed sweet-grass (*Glyceria maxima*), tall robust species
- Reed canary grass (*Phalaris arundinacea*)

Examples

Norfolk Broads. 750 m² island around existing island of Norfolk reed that was being eroded to protect from further erosion. Scirpus and typha – failed, never established. Re-paned with carex and iris – better but still failed because 3 ft waves in winter, conditions too harsh, but booms protected island. Failure – since moved to 2 smaller islands.

Heathrow. Within concrete river system around Terminal 5 to treat runway run-off, probably 6,000 m² as small 60-100 m² sections plus 2 x 500 m².

Severn Trent Water Authority. On reservoirs to improve biological water quality and reduce algae.

Lined lake for EA. Vertical tank rafts, 1.5 m wide and 300 m long strip. Improving lake for Thames Fisheries area.

Hinkey Park. Square ones for EA in Oxford with fish refuge cages (protect from cormorant predation).

Langold Lakes, Nottingham. 8 x 4 m² for nesting habitat for ducks for the Wildlife Trust.

Thames – Charter Key. Private development – lined concrete canal – mitigation for developers.

Cambridge. Planning permission for bird strike on reservoir, mitigate against birds. Floating islands spaced across with shiny discs across.

Gravel pits, St Ives. Tri-lakes with the EA. 16 m² x 6 units with grazing protection and fish predator cages for angling club. Mixed carex and juncus, phragmites don't like small stands.

FILE NOTE

Author: Paul Ellis

Date: 14th February 2008

Project: MIRO

cc:

Telecon with Michael Materne, Louisiana State University Agcenter, USA (001 225 389 0335), 13th February 2008

MM is co-researcher with Charles Sasser, who has been involved in studying flotant in Louisiana for the last 25 years. They are working on the restoration of maidencane-dominated thick-mat flotant on a habitat scale. They are attempting to find the most efficient cost-effective method of restoring damaged areas, which have reverted to open water.

Maidencane (*Panicum hemitomum*) is a very poor seed producer, and the seed it does produce is generally sterile. Thus they have to use clonal/vegetative propagation, using both whole plants and fragments. Techniques have been tested first in greenhouses, then controlled ponds and finally in field conditions where floating marsh is reverting to open water. They deployed several different designs, cumulatively approaching ca. 1 ha made up of small plots. Now in 2nd growing season, trying to establish how far maidencane growth will spread from seeding plots (rafts). Tried a number of different treatments, whole plants better and quicker than fragmented (macerated) plants; rhizomes proved most likely to grow but some growth achieved from aerial-stem fragments.

Whole plants were planted in peat pots to reduce weight and no mineral substrate was introduced. Didn't use coconut matting – very good but expensive. Tried different raft designs including PVC pipe, bamboo with stem boreholes of 2.5" dia, pine timber 2 x 4" size, fir and other wood. Constructed outrigger rafts for flotation, using thin gauge chicken wire for the trays. Over time everything became waterlogged with a reduction in buoyancy and flotation except PVC. From their monitoring it was apparent that efficient plant recovery and growth occurred when the plants were at least at surface level: for example, bamboo sinks slightly, waterlogging plants on the surface. A downside is that PVC doesn't degrade, but will become encased in vegetation so therefore can't be seen once it becomes buried in the substrate. It is also possible to make bigger mats with PVC, biggest is 3 x 3 m (defined by availability of PVC pipe lengths). Booms simple to construct and pipes capped and cemented using standard materials available from plumbing suppliers. They have no problem with shooting at the isolated, secure deployment location. Tried injecting expanding foam insulation material into PVC pipes but this seemed to degrade quickly and become sodden and heavy – not successful.

A mature maidencane mat will self-maintain buoyancy even with accumulation of vegetation and suspended solids. Mature mats can support the weight of a helicopter. A key part of maidencane's buoyancy is the mass of submerged rhizomes which contain many aerenchymous (gas-filled) cells, rather than dependence on methane generation from decaying vegetation.

Flotant mats grow in generally shallow areas with at least 1 m of water beneath, rising up and down. Region is sub-tropical with only a few days when the temperature drops below 32°F, very unusual to have a temperature drop which kills vegetation.

They have grazing problems with 15 lb Nutria (Coypu), introduced 70 years ago as fur animals. MM estimates that 100,000 acres of marsh have been damaged by Nutria grazing. The animals do not just eat the top but the rhizomes as well. Nutria have significantly denuded large areas of marshes. A herbivory guard is therefore essential to give a head start before Nutria can access.

Plants that were uncaged were damaged. A lot of the marshes are flyways for thousands of Blue Geese and Snow Geese which also pose a significant grazing problem but the A-frame chicken wire guard seems efficient. MM thinks the low temperatures of water in UK gravel pits could significantly reduce the growth potential.